AR-008-374

DSTO-TR-0095

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

The temperature to voltage transfer characteristics of the standard turbine inlet temperature averaging sensor for the T56 turbo-prop engine are derived using measured resistance parameters for the 18-thermocouple network. The transfer characteristics of an add-on individual thermocouple temperature sensing circuit are also derived and some of the requirements of the associated signal conditioning circuit are briefly reviewed.

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Distribution /	
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Dist	Avail and / or Special
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Approved for public release

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

DSTO Aeronautical and Maritime Research Laboratory
PO Box 4331
Melbourne Victoria 3001 Australia

Telephone: (03) 626 7000
Fax: (03) 626 7999

AR No. 008-374
November 1994

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EXECUTIVE SUMMARY

1. The Royal Australian Air Force (RAAF), which operates Allison T56 engines in its C-130 Hercules and P-3 Orion turbo-prop aircraft, has experienced problems with the standard turbine inlet temperature (TIT) measuring system which has led to costly maintenance. Similar problems have been experienced by other operators of this engine.

2. Under normal flight conditions, fuel for the T56 engine is scheduled according to closed loop electronic control of average TIT which is sensed using a parallel connection of 18 circumferentially-placed thermocouple probes. Engine fuel control according to TIT measurement is unique to the T56 engine.

3. Inaccurate TIT measurement or an uneven TIT distribution can result in excessively high temperature being experienced by various hot-end components. Early detection and rectification of some simple faults could lead to a significant increase in the lives of some of these components and hence reduce the engine maintenance costs.

4. In view of the limitations of the standard TIT measuring system, the Aeronautical and Maritime Research Laboratory (AMRL) has been examining the potential advantages of, and the requirements for, a system which would take account of individual probe temperatures.

5. In support of this examination, an analysis of the operation of both the standard averaging TIT sensor and of a potential add-on individual probe temperature sensor, under normal and fault conditions, is analysed in this document. The temperature to voltage transfer characteristics for these sensors are derived.

6. Work in support of the analysis included the accurate measurement of loom and probe resistances. In the latter case a means was developed for accurately measuring the probe resistance at typical engine operating temperature.

7. To a good approximation the standard turbine inlet temperature sensor for the T56 engine measures the average of the two loom average thermocouple temperatures (for thermocouples 1 to 9 and 10 to 18 respectively). This relationship is also valid if some thermocouples are open circuit provided the temperature of such thermocouples are excluded from the average.

8. Accurate measurement of the individual-probe temperature distribution can be achieved by measuring the individual-probe electrical outputs with the aid of a high input resistance signal conditioning system. Although the signal sensed at the terminals of any given probe does not truly reflect the actual temperature experienced by the probe, true probe temperatures can be accurately calculated from the signals measured at the terminals of each probe using relationships derived in this report.

9. The analysis contained in this report assists with the understanding of the operation of the standard TIT sensor, and of problems which arise in its application. The analysis also derives relationships which would need to be implemented in an add-on individual probe temperature measuring system.

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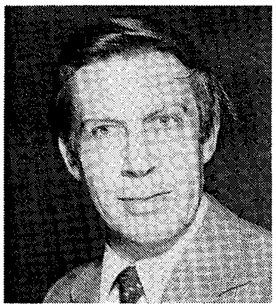

Mr Ken Fraser joined the Aeronautical Research Laboratory (as it was then known) in 1959 after graduating with honours from the University of Melbourne with a Bachelor of Electrical Engineering Degree. Since that time he has worked in various aeronautical fields including crash data recording, weapon kinematics, turbine engine health monitoring, turbine engine control and helicopter life assessment. He was involved in the development and flight demonstration of the world-first "black-box" aircraft crash data recorder which recorded cockpit voice and flight data on a magnetic wire medium. He developed a system for in-flight monitoring of the accumulated fatigue damage to heavily loaded helicopter gears; it was the first time a full fatigue damage calculation, which included component strength characteristics, had been performed during flight in a helicopter. Currently he is a Principal Research Scientist who manages helicopter fatigue life assessment work (structural and mechanical) undertaken by the laboratory on behalf of the Australian Defence Force. He pioneered the setting up , and is now a member, of an Australian Defence Organisation (including all three Services) Working Party which is providing guidance on the applicability of accident data recorders and HUMS (Health and Usage Monitoring Systems) to Australian Defence Force helicopters.

Contents

1. Introduction

Under normal flight conditions, fuel for the Allison T56 turbo-prop engine is scheduled according to closed loop electronic control of average turbine inlet temperature (TIT) which is sensed using a parallel connection of 18 circumferentially-placed thermocouple probes (Figs. 1 and 2). In the taxi or flight-idle ranges the electronic control provides only TIT limiting protection.

In normal flight, the power lever angle (PLA) effectively sets the TIT. Any errors in the measurement of TIT will affect the magnitude of the power (or torque) developed at a given PLA setting.

Inaccurate TIT measurement or an uneven TIT distribution can result in excessively high temperature being experienced by various hot-end components. Early detection and rectification of some simple faults could lead to a significant increase in the lives of some of these components.

TIT averaging is achieved by connecting the electrical terminals of each probe to a common output via a loom with balanced resistance characteristics. In effect, the overall TIT distribution information, inherent in signals present at the terminals of the individual probes, is discarded in the averaging process.

Maintaining thermocouple sensors in serviceable condition over extended periods to measure TIT, typically around 1000°C, is very difficult. Engine fuel control according to TIT measurement is unique to the T56 engine and has had an associated heavy and costly maintenance demand on hot-end components. Incorrect measurement of average TIT due to faulty thermocouples, and the inability of the standard sensing system to identify an uneven temperature distribution, have largely contributed to these problems. The Royal Australian Air Force (RAAF), which operates T56 engines in its C-130 Hercules and P-3 Orion aircraft, has experienced such problems. On a world-wide basis there are about 15000 T56 engines in service and the problems referred to above are well recognised by all operators of this engine.

To provide a better understanding of the problems which arise in the measurement of TIT for the T56 engine, the operation of the standard averaging TIT sensor, under normal and fault conditions, is analysed in this document. The temperature to voltage transfer characteristics for that sensor are derived.

In view of the limitations of the standard TIT measuring system, the Aeronautical and Maritime Research Laboratory (AMRL) has been examining the potential advantages of, and the requirements for, a system which would take account of individual probe temperatures. In support of this examination, the temperature to voltage transfer characteristics of the individual probe outputs are also derived herein.

2. Resistance of Hot-End Thermocouple Circuit

2.1 General

The hot-end thermocouple circuit for the T56 engine comprises two independent turbine inlet temperature (TIT) sensing circuits, one of which is referred to by the engine manufacturer as the Temperature Datum circuit and the other as the Indicator circuit. The Temperature Datum circuit is used by the electronic controller for scheduling fuel flow to the combustors and the Indicator circuit is used for a cockpit TIT display. Three total temperature thermocouple probes are placed in each of the six combustor liners giving a total of 18 probes (Fig. 3). Each probe has two electrically-isolated chromel-alumel hot junction elements; one is connected to the Temperature datum circuit and the other to the Indicator circuit. Both the Temperature Datum and the Indicator circuits are designed to sense the average of the 18 temperatures sensed by their respective probe elements. The hot-end circuit comprises the 18 dual-element thermocouple probes and an associated harness which is configured to provide temperature averaging. The harness (Fig. 2) comprises two looms enclosed in semi-circular metal housings of rectangular cross section. One of the looms is connected to probes 1 to 9 and the other to probes 10 to 18. Other variants of the harness have been used on T56 engines but these variants will not be considered in this document. Each temperature averaging loom interconnects the four output terminals on any given thermocouple probe to the corresponding outputs from each of the other eight thermocouple probes. In effect each loom has 9×4 input wires and 1×4 output wires. The arrangement of electrical connections to each loom is depicted in Fig. 4. The corresponding outputs of the two looms are joined together at the terminal block (Fig. 2).

Average TIT is obtained by measuring the net emf (electromotive force) developed at the output of the terminal block. To accurately sense the average TIT, it is essential that the electrical resistance values of corresponding paths of the temperature averaging looms be closely matched.

Resistance measurements were made on a batch of thermocouple probes and a temperature signal averaging loom to enable the equivalent circuit of the sensor to be defined and to check the resistance matching accuracy. The results of these measurements are examined in the following sub-sections.

2.2 Thermocouple Probe Internal Resistance

Some resistance measurements were performed on a small sample of probes at room temperature and some were also performed at elevated temperatures to simulate in-flight conditions. When considering how close the signal measured at the probe terminals reflects the actual temperature sensed by the probe (Sec. 5), account needs to be taken of the significant increase in probe resistance which occurs as the temperature

of the probe is raised from ambient to engine operating temperature. That increase in probe resistance has negligible effect on the average temperature measured, provided similar variations with temperature occur in all probes (ie. circuit balance is maintained).

Accurate measurement of probe resistance is difficult as considerable care is necessary to ensure that the contact resistance between the probe and the measuring circuit is much lower than the probe resistance. Conventional multimeters measure resistance by applying a DC voltage to the circuit whose resistance is to be measured. Thermal effects can be troublesome even when the complete probe is at room temperature. When a temperature gradient is applied across the probe (when simulating in-flight conditions) the DC voltage method becomes unworkable. To enable rapid and reliable measurements to be made at elevated temperatures an AC ratio technique, which effectively eliminates the effect of the DC or slowly varying thermally induced voltage, was used. The measuring technique is detailed in Appendix 1.

The internal resistance values for three new thermocouple probes and three which had been in service ("old") were measured at room temperature. The results of these measurements are summarised in Table 1. This small sample yields the following:

Range for new thermocouples	:	0.0520 to 0.0604 ohm
Mean for new thermocouples	:	0.0558 ohm
Range for old thermocouples	:	0.0594 to 0.0684 ohm
Mean for old thermocouples	:	0.0638 ohm
Overall mean	:	0.0598 ohm
Overall standard deviation (SD)	:	0.00518 ohm
Coefficient of variation (SD/mean)	:	8.66%

The conclusions which can be drawn from measurements on this small batch of probes are very limited. The internal resistance of the old probes was higher than that for the new ones. The spread of measured values was within – 13.0% to + 14.4% of the overall mean and the overall coefficient of variation was 8.7%.

Measurements of probe internal resistance at elevated temperatures (Appendix 1) indicated that the resistance is expected to rise approximately 25% from the above value when the operating temperature is raised to 1000°C (typical for in-flight conditions). The corrected overall mean probe resistance thus becomes 0.0748 ohm at 1000°C.

The manufacturer indicates[1] that thermocouple probes with internal resistance outside the range 0.045 to 0.085 ohm at room temperature should be rejected. This implies an acceptable range at 1000°C of 0.056 to 0.106 ohm. The measurements detailed above were all well within the specified limits. In the following sections the value 0.075 ohm will be used for circuit analysis purposes.

2.3 Temperature Averaging Loom Resistance Parameters

Input-to-output and input-to-input resistance values for the temperature signal averaging loom (thermocouple probes 1 to 9) were measured for the Indicator section of a new loom. The electrical interconnections within the Indicator loom are depicted in Fig. 5 and the measured resistance values for one section of the Indicator (that for connection to probes 1 to 9) are given in Table 2. The measurements yield the following ranges and mean values.

Range for chromel input-to-output	:	1.436 to 1.439 ohm
Mean for chromel input-to-output	:	1.438 ohm
Variation from mean for chromel input-to-output	:	– 0.10 to + 0.10 %
Coefficient of variation	:	0.091%
Range for chromel input-to-input	:	1.343 to 1.347 ohm
Mean for chromel input-to-input	:	1.345 ohm
Variation from mean for chromel input-to-input	:	– 0.13 to + 0.16 %
Coefficient of variation	:	0.111%
Range for alumel input-to-output	:	0.600 to 0.604 ohm
Mean for alumel input-to-output	:	0.602 ohm
Variation from mean for alumel input-to-output	:	– 0.30 to + 0.37 %
Coefficient of variation	:	0.182%
Range for alumel input to input	:	0.556 to 0.560 ohm
Mean for alumel input-to-input	:	0.558 ohm
Variation from mean for alumel input-to-input	:	– 0.34 to + 0.38 %
Coefficient of variation	:	0.202%

The above values demonstrate very good resistance matching for the Indicator section of the thermocouple loom for which the detailed measurements were made. While the input-to-input resistance values given in Table 2 are all referred back to the input terminals for probe 1, spot checks indicated that the resistance value for any pair of inputs conformed to the same range. A check of the resistance values for the other section of the Indicator loom (for connection to probes 10 to 18) indicated that the values closely conformed to the ranges listed above.

Spot checks of the resistance values for the Temperature Datum section of the same loom indicated that the measured values were within 0.1% of the mean values tabulated above for the Indicator section.

3. Equivalent Electrical Circuit for Standard Turbine Inlet Temperature Sensor

3.1 General Approach

The thermocouple probe and the loom resistance values given in Sec. 2 can be used to define an equivalent electrical circuit for the TIT sensor. Since the standard TIT sensor is formed from a network of thermocouple junctions it is convenient to first look at the temperature/voltage transfer characteristic of an isolated thermocouple junction.

3.2 Circuit Representation of a Single Thermocouple Junction

Thermocouple theory[2] indicates that when two wires composed of dissimilar metals are joined, a voltage (theSeebeck voltage) which is a function of the junction temperature and the composition of the two metals, will be generated between the wires. An isolated thermocouple junction is illustrated in Fig. 6a and its equivalent electrical circuit in Fig. 6b where e_n is the Seebeck voltage (the open circuit voltage of the thermocouple junction) and R_{TH} is the thermocouple internal resistance.

The Seebeck voltage e_n may be related to junction temperature T_n by the generalised function:

$$e_n = f(T_n) + b_0 \tag{1}$$

where $f(T_n)$, for convenience, is defined to have zero value when (T_n)=0°C.

b_0 is a constant equal to the open circuit voltage developed across the junction at 0°C.

$f(T_n)$ may be represented by a look-up table of values or analytically by a polynomial:

$$f(T_n) = b_1 T_n + b_2 (T_n)^2 + \ldots.. \tag{2}$$

where b_1, b_2 etc. are constants.

To represent the temperature to voltage relationship of a standard chromel-alumel thermocouple to an accuracy of ± 0.7°C over the temperature range 0°C to 1370°C, an eighth order polynomial is required[2].

The Seebeck voltage across a single junction cannot be simply measured, as the act of connecting a voltmeter (for example) across the terminals to measure it (Fig. 6c) will introduce further dissimilar metal junctions (Cr-Cu and Cu-Al for a Cr-Al thermocouple connected to an instrument with copper leads). The Seebeck voltages developed across these additional junctions will obscure the open circuit voltage across the junction of interest. The voltage read will be $f(T_n) - f(T_x)$ where T_n is the thermocouple junction temperature and T_x is the temperature at the output terminals. If $T_n = T_x$ the measured voltage will be zero.

Thermocouple circuit analysis is usually performed using a closed-circuit representation involving a hot and a cold junction. With that approach only temperature differences and voltage differences (which are measurable) need to be considered. However the analysis of a more complex network of interconnected thermocouples is most easily done by summing the effect of individual thermocouple junction equivalent circuits of the type shown in Fig. 6b.

Over a limited temperature range the temperature/voltage relationship can be approximated by a linear function:

$$e_n = mT_n + k \tag{3}$$

where m and k are constants.

For the T56 application, it is appropriate to examine the parameters of equation 3 which provide a good approximation to the temperature/voltage relationship in the vicinity of 1000°C operating temperature. For the standard chromel-alumel thermocouple the slope m at this temperature is 38.91 microvolt/°C and the output relative to a cold junction at 0°C is 41.269 mV. The open circuit junction voltage in the 1000°C region can thus be expressed as:

$$\begin{aligned} e_n &= 0.03891\,(T_n - 1000) + 41.269 + b_0 \\ &= 0.03891 T_n + 2.359 + b_0 \end{aligned} \tag{4}$$

where e_n is given in mV;

b_0 is the open circuit voltage (mV) generated across a junction held at 0°C (as for equation 1).

Hence $m = 0.0389$ mV/°C

$k = b_0 + 2.359$ mV

In practice the numeric value of b_0 is not important as it will always cancel out when a closed circuit is formed. It is to be noted that k is not equal to b_0, since the linear approximation to $f(T_n)$, valid in the vicinity of 1000°C, produces a substantial error (2.359 mV) at 0°C.

At 900°C and 1100°C the standard chromel-alumel thermocouple provides outputs of 37.325 mV and 45.108 mV respectively relative to a cold junction at 0°C. The linear approximation of equation 4 will provide correct reading at 1000°C but will yield an error of about –1.35°C at 900°C and 1100°C.

3.3 Derivation of Transfer Characteristics of Standard Temperature Sensor

Using average resistance values derived in Sec. 2 and assuming perfect loom resistance symmetry, the TIT sensor circuit of Fig. 7 can be inferred for operation in the region of 1000°C. In that figure chromel terminals and wire resistance values are given an "X" label, whereas alumel terminals and wire resistance values are given a "Y" label. For convenience the loom connected to probes 1 to 9 is designated loom A and

the loom connected to probes 10 to 18 is designated loom B. R_{1X} and R_{1Y} are set to half the measured input-to-input resistance of the chromel and alumel inputs to the respective looms. Subtraction of these values from the measured input-to-output resistance provides the R_{JAX} and R_{JAY} resistance values.

Provided all circuit elements behave linearly it follows, from basic circuit theory, that the circuit "seen" at the terminals of any arbitrarily defined branch may be represented by a single voltage source, equal to the open circuit voltage developed at the branch terminals, in series with a single impedance equal to the net output impedance of the circuit (calculated simply by replacing all voltage generators with a zero resistance). However, as discussed in Sec. 3.2, care needs to be exercised in interpreting any voltage checked by measurement between chromel and alumel wires.

The portion of the circuit of Fig. 7 which performs the averaging function for thermocouples 1 to 9 may be represented as in Fig. 8a where G_1 etc. are the net conductances (inverse of net resistance) for each leg.

$$G_1 = \frac{1}{R_{TH1} + R_{1X} + R_{1Y}} \tag{5}$$

The circuit of Fig. 8a can be represented by a single voltage generator circuit as illustrated in Fig. 8b where:

$$e_A = \frac{e_1 G_1 + e_2 G_2 + \ldots + e_9 G_9}{G_1 + G_2 + \ldots + G_9} \tag{6}$$

The net conductance G_A of the loom connected to probe inputs 1 to 9 (Figs. 8b and 8c) is given by:

$$G_A = \frac{1}{\frac{1}{G_{A1}} + R_{JAX} + R_{JAY}} \tag{7}$$

where $\qquad G_{A1} = G_1 + G_2 + \ldots + G_9$

Similar relationships apply for the second loom:

$$e_B = \frac{e_{10} G_{10} + e_{11} G_{11} + \ldots + e_{18} G_{18}}{G_{10} + G_{11} + \ldots + G_{18}} \tag{8}$$

$$G_B = \frac{1}{\frac{1}{G_{B1}} + R_{JBX} + R_{JBY}} \tag{9}$$

where $\qquad G_{B1} = G_{10} + G_{11} + \ldots + G_{18}$

The combined effect of both looms (Fig. 8c) provides an equivalent single hot junction thermocouple as depicted in Fig. 8d. The net voltage e_H which is generated is given by:

$$e_H = \frac{e_A G_A + e_B G_B}{G_A + G_B} \tag{10}$$

In general terms:

$$e_H = a_1 e_1 + a_2 e_2 + ... + a_{18} e_{18} \tag{11}$$

where a_1, a_2 etc. are the transfer coefficients given by:

$$a_n = \frac{G_n G_A}{G_{A1}(G_A + G_B)} \qquad \text{for n in range 1 to 9} \tag{12}$$

$$a_n = \frac{G_n G_B}{G_{B1}(G_A + G_B)} \qquad \text{for n in range 10 to 18} \tag{13}$$

It is readily seen that:

$$a_1 + a_2 + ... + a_{18} = 1 \tag{14}$$

In temperature terms (using equation 1):

$$\begin{aligned} e_H &= f(T_H) + b_0 \\ &= a_1 e_1 + a_2 e_2 + ... + a_{18} e_{18} \\ &= a_1\{f(T_1) + b_0\} + ... + a_{18}\{f(T_{18}) + b_0\} \\ &= \sum_{i=1}^{18} f(T_i) + b_0 \sum_{i=1}^{18} a_i \\ &= \sum_{i=1}^{18} f(T_i) + b_0 \end{aligned} \tag{15}$$

Hence

$$f(T_H) = \sum_{i=1}^{18} a_i f(T_i) \tag{16}$$

If the linear relationship of equation 2 is assumed to apply in the region of interest, then:

$$\begin{aligned} e_H &= mT_H + b \\ &= m\sum_{i=1}^{18} a_i T_i + b \end{aligned}$$

$$T_H = \sum_{i=1}^{18} a_i T_i \tag{17}$$

This relationship is quite general and does not require the transfer coefficients a_n (n = 1 to 18) to be equal. In some of the analyses to be considered in later sections all the transfer coefficients will not be equal.

For perfectly matched looms and probe internal resistances $\dfrac{G_n}{G_{A1}} = \dfrac{G_n}{G_{B1}} = \dfrac{1}{9}$, $G_A = G_B$ (ie. looms of identical resistance), $a_n = \dfrac{1}{18} = 0.056$, and e_H becomes simply:

$$e_H = \frac{e_1 + e_2 + ... + e_{18}}{18} \tag{18}$$

Provided the characteristics of the thermocouple probes are the same and the loom resistances are properly balanced, true voltage averaging is achieved (a_1 to a_{18} equal to $\frac{1}{18}$). If the temperature-to-voltage relationships for all thermocouples are also matched, true temperature averaging will also be achieved as described by the following equation.

$$T_H = \frac{T_1 + T_2 + ... + T_{18}}{18} \tag{19}$$

The internal resistance of the equivalent hot end thermocouple R_H, as seen looking back from the terminal block towards the thermocouple probes, is:

$$R_H = \frac{1}{G_A + G_B} \tag{20}$$

For the resistance values given in the balanced circuit of Fig. 7 the following parameter values apply:

$$\begin{aligned} G_n &= \frac{1}{0.075 + 0.672 + 0.279} \; mho \\ &= 0.975 \; mho \end{aligned}$$

$$\begin{aligned} G_{A1} &= G_{B1} \\ &= 9(0.975) \; mho \\ &= 8.775 \; mho \end{aligned}$$

$$\begin{aligned} G_A &= G_B \\ &= 0.832 \; mho \end{aligned}$$

$$R_H = 0.601 \; ohm$$

The temperature transfer coefficients for the TIT sensor are summarised together with the calculated output resistance in Table 3. A Turbo Pascal computer program[3] was written to allow these and similar calculations to be simply made.

To complete the TIT indicating circuit, the cold junction and associated circuit needs to be added to the circuit of Fig. 8d. The cold junction for the T56 engine TIT Indicator is located in the cockpit area (ie. remotely from the engine). The Indicator for the C-130 and P-3 aircraft acts as a voltage measuring device which presents negligible loading on the engine-mounted hot junction circuit. A compensating arrangement simulates a cold junction at 0°C. The compensating voltage is derived from the

voltage developed across a bridge circuit which contains a temperature-dependent resistive component. The function of this circuit will be examined more closely below.

Chromel and alumel wires are run from the engine to the cockpit TIT Indicator where they are each joined with copper wires to form an effective chromel-alumel cold junction (Fig. 9a). The cold junction temperature T_L is not controlled, and hence it will follow any variations in cockpit temperature. The open circuit thermal emf generated at the cold junction (Fig. 9b) is e_L where:

$$e_L = f(T_L) + b_0 \tag{21}$$

The net thermal emf for the complete system (Figs. 9c and 9d) is $(e_H - e_L)$.

$$e_H - e_L = f(T_H) - f(T_L) \tag{22}$$

The cockpit circuit for the TIT Indicator in the C-130 Hercules aircraft can be functionally subdivided (Fig. 10a) into a *cold junction compensation circuit* and an *output amplifier circuit*.

The function of the cold junction compensation circuit is to add a compensating emf to the net thermal emf to produce the same overall effect as a cold junction held at a constant 0°C. A simplified representation of the cold junction compensation circuit is given in Fig. 10b. The compensation voltage e_C is derived from the output of a bridge circuit powered with an isolated DC voltage V_{AA} (obtained from the 115 VAC 400 Hz aircraft supply via a conventional transformer, rectifier and voltage regulator circuit).

The compensation voltage is given approximately by:

$$e_C = 0.5\,(R_{BA} - R_{BB})\ mV \tag{23}$$

where resistance values are given in ohms.

The resistance term $(R_{BA} - R_{BB})$ has an appropriate positive temperature coefficient to closely yield:

$$\begin{aligned} e_H - e_L + e_C &= f(T_H) \\ e_C &= f(T_L) \end{aligned} \tag{24}$$

Series resistance R_F and shunt capacitance C, provide low pass filtering of the combined output signal. The net signal source resistance R_S is given approximately as:

$$\begin{aligned} R_S &\approx R_H + R_W + R_F + R_{BA} + R_{BB} \\ &\approx R_F + R_{BA} + R_{BB} \\ &\approx 1500\ ohm \end{aligned}$$

The effective time constant of the low pass filter (assuming the amplifier input resistance R_L [Fig. 10c] is much higher than R_S) is $R_S C$ (84 ms) which represents 1.9 Hz cutoff frequency.

The output e_O of the low level signal circuit (Fig. 10c) is given by:

$$e_O = \frac{R_L}{R_S + R_L}(e_H - e_L + e_C) \tag{25}$$

A simplified schema of the output amplifier is drawn in Fig. 10d. A chopper amplifier (with 400 Hz switching frequency) provides the control input for a servo motor driven indicator. Mechanical feedback adjusts potentiometer R_V (which is mechanically coupled to the Indicator servo motor) till the feedback voltage e_f virtually balances out the input voltage. In simple terms (ignoring any lead or lag elements within the amplifier system) the feedback voltage is given by:

$$\begin{aligned} e_f &= kV_{BB} \\ &= Ae_g \end{aligned} \tag{26}$$

where k is mechanically controlled within the range $0<k<1$;

e_g is the voltage input to the chopper amplifier (Fig. 10d).

A is the effective loop gain of the output amplifier.

Simple analysis of the amplifier circuit (Fig. 10d) yields:

$$\begin{aligned} e_g &= e_O - e_f \\ e_f &= \frac{A}{1+A} e_g \end{aligned} \tag{27}$$

For $A >> 1$ $\quad e_f \approx e_O$

The effective input resistance R_L of the amplifier is given by:

$$\begin{aligned} R_L &= \frac{e_O}{i_O} \\ &= \frac{e_O}{e_g} R_{in} \\ &= (A+1)R_{in} \end{aligned} \tag{28}$$

The negative feedback greatly increases the effective input resistance. The values of A and R_{in} are not available to the author but it can be assumed $R_L >> R_S$. From equation 25 it follows that:

$$e_O \approx e_H - e_L + e_C \tag{29}$$

and for "perfect" cold junction compensation:

$$e_O = f(T_H) \tag{30}$$

Many engine thermocouple temperature sensing systems in current service in aircraft make direct use of the thermally generated emf of the thermocouple circuit to provide the current required to indicate the measured temperature via moving-coil cockpit meters. Because of the relatively low input resistance presented by such cold junction circuits, the voltage drop across the signal conductors from the engine to the cockpit indicator needs to be taken into account.

4. Effect of some Faults on Standard Turbine Inlet Temperature Sensor Circuit Performance

4.1 Open Circuit Thermocouple Probe

One of the most common T56 TIT electrical circuit problems encountered in service is a burnt out hot junction on one or more thermocouple probes. Usually an open circuit develops due to the breaking of the sensing element adjacent to the weld of the dissimilar metals. There is considerable in-service evidence which indicates that when open-circuit probes are replaced, usually both the Temperature Datum and the Indicator junctions have both developed an open-circuit. Assuming that the development of an open-circuit is caused primarily because the probe is subject to an excessively high local temperature, the failure of both junctions could only be explained if the failure-temperature of each were closely matched.

The effect of an open-circuit thermocouple probe on sensed average TIT can be easily analysed. For convenience consider the effect of an open-circuit in probe No. 1. This simply means an analysis as in Sec. 3.3 with G_1 equal to zero.

Referring to equations 12 and 13, the net effect of the open circuit in the No. 1 thermocouple probe will be:

(a) $\dfrac{G_n}{G_{A1}}$ will change from $\dfrac{1}{9}$ to $\dfrac{1}{8}$.

(b) $\dfrac{G_n}{G_{B1}}$ will remain unchanged at $\dfrac{1}{9}$.

(c) There will be a small change in the value of G_A but taking $G_A = G_B$ will be a fairly good approximation.

(d) Transfer coefficient a_1 will become 0; to a good approximation a_2 to a_9 will increase to $\dfrac{1}{16}$ and a_{10} to a_{18} will remain at $\dfrac{1}{18}$.

Hence, to a good approximation, the sensed temperature will be the average of the average temperatures sensed by each of the looms (refer to equation 16).

$$T_H = \frac{T_A + T_B}{2} \tag{31}$$

where T_A is the average temperature sensed by loom A,

and T_B is the average temperature sensed by loom B.

$$T_H = \frac{T_2 + \ldots + T_9}{16} + \frac{T_{10} + \ldots + T_{18}}{18} \tag{32}$$

$$= 0.0625(T_2 + \ldots + T_9) + 0.0556(T_{10} + \ldots + T_{18}) \tag{33}$$

In practice there are slight effects on the a_i transfer coefficients (equation 16) due to the resistance unbalance of the two looms arising from the open circuit thermocouple probe. The Turbo Pascal computer program[3] enabled these effects to be readily calculated. The calculated values given in Table 4 indicate that the changes in the factors shown in equation 33 are very small (0.0621 in lieu of 0.0625 and 0.0559 in lieu of 0.0556).

Note that the value of T_H which is measured when a thermocouple probe goes open circuit is not the average temperature sensed by the remaining 17 probes, although it may be close to that value. If an equal number of probes become open circuit in each of the two looms, T_H will then revert to the average temperature sensed by the remaining probes.

The shift in measured temperature T_H arising from an open circuit thermocouple probe will be dependent on the pre-fault temperature of the open-circuit probe.

The fall in measured temperature is given by the theoretical difference, T_{HD} say, in the average temperature for normal operation (equation 19) and for operation with the No. 1 thermocouple probe open circuit (a negative result for T_{HD} would mean a rise in temperature for the polarity chosen for the difference):

$$T_{HD} = \frac{T_1 - T_{A2}}{18} \tag{34}$$

$$T_{HD} = \frac{T_1 - T_{A1}}{16} \tag{35}$$

where T_1 is the pre-fault junction temperature of thermocouple No. 1;

T_{A2} is the post-fault average temperature sensed by loom A;

T_{A1} is the pre-fault average temperature sensed by loom A.

$$T_{A1} = \frac{T_1 + \ldots + T_9}{9} \tag{36}$$

$$T_{A2} = \frac{T_2 + \ldots + T_9}{8} \tag{37}$$

Thermocouple probe No. 1 has been chosen simply for convenience. In general the shift in temperature due to a probe going open circuit is:

$$T_{HD} = \frac{T_R - T_{LR}}{2M} \tag{38}$$

where T_R is the pre-fault junction temperature read by the R^{th} thermocouple;

T_{LR} is the pre-fault average temperature sensed by the loom to which the R^{th} thermocouple is connected;

M is the post-fault number of active thermocouples remaining in the loom to which the R^{th} thermocouple is connected.

For example, if the faulty thermocouple probe was reading 100°C higher than the average for the remaining probes connected to the same loom, the shift in the measured average temperature would be 6.25°C (if no additional probes had previously become open circuit). Of course there would be no observed change in measured average TIT if the temperature sensed by the faulty probe, at the time the open circuit is developed, is equal to the average temperature sensed by the remaining probes in the same loom.

It is unlikely that the magnitude of the shift in average TIT resulting from a probe developing an open circuit will be very repeatable. For example, a repeatable 6°C fall could arise only if the open circuit developed when the probe temperature was about 100°C above the average temperature sensed by the associated loom (a fairly arbitrary value).

4.2 Broken Thermocouple Probe Tip

Another fault which can occur in T56 thermocouple probes is a "broken tip". In this case the electrical integrity of the probe remains intact but the lower extremity of the outer casing is broken off, usually in the vicinity of the hot gas flow inlet sampling holes (Fig. 1). The effect of such a fault is that the gas sample will no longer be taken from deep within the gas path where the temperature is greatest but will experience the relatively cool environment at the periphery of the combustion chamber where the cooling air enters the probe (Fig. 1). The broken tip will cause the cooling air to exit in the vicinity of the thermocouple junctions rather than at the normal location at the tip of the probe casing. Hence the temperature "seen" by the thermocouple probe will fall. The manufacturer indicates that a fall in average TIT of 22°C is to be expected if such a fault occurs. This implies that the fall in temperature experienced by a probe which loses a tip will be 396°C (18×22). It might be expected that the magnitude of the temperature fall associated with this type of failure may be fairly repeatable.

For a given fall in temperature sensed by a probe with a broken tip the effect on measured average TIT will be modified if there are one or more open circuit probes on the same loom. For example the expected fall in measured TIT will be 25°C (396/16) if one probe in the associated loom is open circuit, 28°C (396/14) if two probes are open circuit etc.

4.3 Other

Another T56 TIT electrical circuit problem which is sometimes encountered in service is a short circuit of a thermocouple probe to engine ground. The effect of such a fault would be very difficult to predict and may vary from one aircraft installation to another. The Indicator circuit is isolated from aircraft ground, so in theory the normal mode signal should be unaffected by single point grounding. However the changed common mode impedance coupled with extraneous ground noise signals are likely to affect the measured TIT.

The effect of an increase in contact resistance at the thermocouple probe terminals (ie. between the probe studs and the loom lugs) can be easily calculated. The effect will be the same as an increase in internal resistance of the probe. From equation 12 it follows that a 0.01 ohm increase in contact resistance (equivalent to a 13 % increase in nominal probe resistance) will change the transfer coefficient a_n from 0.1111 to 0.1101 (ie. a difference of 0.001). At 1000°C this would reduce the measured temperature reading for the particular probe by only 1°C and have negligible effect on the measured average TIT value. The much higher loom resistances therefore serve to render the measurement system fairly insensitive to probe terminal contact resistance and probe internal resistance variations.

One of the most serious causes of temperature measurement error is the change in thermocouple temperature/voltage characteristic (equation 3) which can occur over time. This is an ageing effect and is influenced by the harshness of the environment in which the probe operates.

All faults which have been referred to so far reflect an error in TIT measurement. There are of course faults (eg. a blocked fuel nozzle) which will result in an uneven temperature distribution around the engine. Such faults do not give rise to an error in the measured average TIT, but could be readily detected if individual probe temperatures were measured.

5. Equivalent Electrical Circuit for Individual Turbine Inlet Temperature Sensor

Individual thermocouple temperatures could be sensed, on engines installed in aircraft or in test facilities, by an add-on circuit comprising additional electrical wires from each of the 18 pairs of TIT Indicator probe terminals to a specially installed signal conditioning system. Because the loom input resistance is low enough to have a loading effect on probe outputs, the voltage generated at the terminals of any probe will contain some residual components from other probes connected to the loom. This

means that the signal appearing at the terminals of any given probe will not exactly reflect the temperature sensed by that probe*.

The equivalent circuit of Fig. 11 can be used to calculate the voltage e_{18M} appearing at the terminals of thermocouple probe No. 18. This circuit assumes the nominal values of probe and loom resistances defined in Fig. 7 apply. Analysis of the Fig. 11 circuit with the aid of the computer program[3] yields:

$$e_{18M} = 0.0004(e_1 + ... + e_9) + 0.0077(e_{10} + ... + e_{17}) + 0.9346\, e_{18} \tag{39}$$

In temperature terms this is equivalent to:

$$T_{18M} = 0.0004\,(T_1 + ... + T_9) + 0.0077(T_{10} .... + T_{17}) + 0.9346\, T_{18} \tag{40}$$

Probe No. 18 has been chosen simply for convenience. In general the temperature measured at the terminals of any given probe is:

Measured temperature
= 0.9346 (Actual probe junction temp)
\+ 0.0616 (Average temp sensed by other probes connected to same loom)
\+ 0.0036 (Average temp sensed by probes connected to other loom) (41)

The relationship between measured and true temperatures can be conveniently expressed in matrix form:

$$T_M = A T_T \tag{42}$$

where T_M is an 18-element measured temperature column matrix $T_{1M} .... T_{18M}$;

T_T is an 18-element true temperature column matrix $T_1 .... T_{18}$;

A is an 18x18 transfer coefficient square matrix.

Matrix A transfer coefficients are provided in Table 6. Note that perfect matching of probe internal resistances and loom resistances are assumed in calculating these coefficients. Using the Table 6 values, the measured temperatures can be simply expressed:

$$T_{nM} = 0.9269\, T_{nT} + 0.0693 T_A + 0.0036 T_B \quad \text{for n in range 1 to 9} \tag{43}$$

$$T_{nM} = 0.9269\, T_{nT} + 0.0693 T_B + 0.0036 T_A \quad \text{for n in range 10 to 18} \tag{44}$$

where T_{nM} is the measured temperature of thermocouple No. n;

T_{nT} is the true temperature of thermocouple No. n;

T_A is the average of the true temperatures of thermocouples Nos. 1 to 9;

* This effect is quite separate from the deliberate departure from the standard temperature to emf relationship sometimes introduced in gas turbine engine thermocouple probes by the engine manufacturer. The usual purpose of such a departure is to allow a small increase in operating temperature for uprated engines to be implemented without changing the standard thermocouple sensing circuits. In effect, this will mean that the temperature read from the standard cockpit Indicator will have a deliberature but known offset from the true value.

T_B is the average of the true temperatures of thermocouples Nos. 10 to 18.

The inverse relationship between true and measured temperatures is given by:

$$T_T = \overline{A} T_M \tag{45}$$

where $\overline{A}$ is the inverse of matrix A.

The transfer coefficients for the inverse matrix were calculated using the computer program[3] and are given in Table 7.

Using the Table 7 values, the true temperatures can be simply expressed in terms of the measured temperatures:

$$T_{nT} = 1.0789 T_{nM} - 0.0756 T_{AM} - 0.0036 T_{BM} \qquad \text{for n in range 1 to 9} \tag{46}$$

$$T_{nT} = 1.0789 T_{nM} - 0.0756 T_{BM} + 0.0036 T_{AM} \qquad \text{for n in range 10 to 18} \tag{47}$$

where T_{AM} is the average of the measured temperatures for thermocouples 1 to 9;
T_{BM} is the average of the measured temperatures for thermocouples 10 to 18.

The relationships of equations 46 and 47 can be used to calculate the actual temperatures experienced by the thermocouple probes.

According to equation 40, each measured temperature has a residual component (6.5% approximately for a probe resistance of 0.075 ohm at 1000°C) due to inputs from other thermocouples. The magnitude of the residual component is proportional to the probe internal resistance which will vary with temperature and may vary with aging. As indicated in Sec. 2.2, the acceptable limits for probe resistance are 0.045 to 0.106 ohm. This implies that the residual component limits would be 3.9 to 9.2%.

To a good approximation (equation 40) the contribution of the thermocouple probes which are not connected to the same loom as the probe under consideration, can be taken as zero.

The average value of the true temperatures is equal to the average value of the measured temperatures (this is apparent if the column elements of Tables 6 and 7 are added). Hence:

$$T_1 + \ldots + T_{18} = T_{1M} + \ldots + T_{18M} \tag{48}$$

There is a small but negligible cross coupling term between temperatures measured on one loom and temperatures measured on the other. Hence to a very good approximation (ignoring the cross coupling term) the following also apply:

$$T_A = T_{AM} \tag{49}$$

$$T_B = T_{BM} \tag{50}$$

Although the signal sensed at the terminals of any given probe does not truly reflect the actual temperature experienced by the probe, true probe temperatures can be accurately calculated from the signals measured at the terminals of each probe using the relationships derived in this section.

6. Effect of some Faults on Individual Turbine Inlet Temperature Sensor Circuit Performance

6.1 Open Circuit Thermocouple Probe

The signal sensed at the terminals of a thermocouple probe which has become open circuit is given by the referenced computer program[3]. For convenience, probe No. 18 is considered to become open circuit. The transfer coefficients for the signal sensed at the terminals of that probe are given in Table 5. The results may be expressed as:

$$T_{18M} = 0.053T_A + 0.947T_B \tag{51}$$

where T_A is the average temperature sensed by probes 1 to 9

and T_B is the average temperature sensed by probes 10 to 17.

To a first approximation the measured temperature, as deduced from the signal appearing at the terminals of an open circuit probe, will be the average temperature sensed by the loom to which the open circuit probe is attached (equation 51 indicates the other loom will contribute about 5 %). Experimental work, performed at a T56 engine test facility on an individual TIT measuring system, verified this behaviour. Fig. 12 demonstrates that when probe No. 7 was made open circuit the temperature sensed at the probe terminals was very close to the average temperature sensed by the loom A probes. In this test the average temperature sensed by the loom A probes was higher (by about 12°C after the open circuit was introduced) than that sensed by the loom B probes.

The measured pre-fault temperature for probe No. 18 is given by equation 40. No change in measured temperature will occur unless the probe which became open circuit was reading a temperature which was different from the average TIT at the time the open circuit developed.

For example assume actual probe temperatures T_1 to T_{17} are equal to T, and T_{18} is equal to $(T + 100)$, at the time the open circuit develops. Equation 40 indicates that T_{18M} will be $(T + 93.5)$ prior to the fault occurring and equation 50 indicates that it will be T after the fault occurs. Hence in this special case a 100°C temperature difference will be reflected as a 93.5°C change in measured temperature. Such a significant change in the TIT profile could be readily detected with a suitable individual probe temperature measuring system.

Probe No. 18 has been selected for convenience only; similar relationships apply for the other probes.

The output resistance measured at the probe terminals will rise from the normal value of 0.0701 ohm (0.075 ohm probe internal resistance assumed) to 1.0724 ohm when the probe becomes open circuit. This change could be used for flight-line in-situ checking for probe continuity when the engine is not running.

An open circuit on one of the probes (T_{18} say) will also have a small effect on the temperatures measured by the "good" thermocouples. If, using the above example, actual probe temperatures T_1 to T_{17} are assumed to be equal to T, and T_{18} to be equal to $(T + 100)$, at the time the open circuit develops then, using equation 51, the following will apply approximately:

Change in temperatures measured by good probes on same loom as the open circuit thermocouple

= 0.0616 × (change in average temperature sensed by other probes connected to same loom)

$$= \frac{0.0616 \times 100}{8} \text{ °C} \qquad = \qquad 0.68 \text{ °C}$$

and similarly

Change in temperatures measured by good probes on the loom which does not include the open circuit thermocouple

= 0.0036 × (change in average temperature sensed by the loom to which the open circuit thermocouple is connected)

$$= \frac{0.0036 \times 100}{8} \text{ °C} \qquad = \qquad 0.04 \text{ °C}$$

It follows that the side effect of an open circuit probe on the temperatures measured by the other probes is negligible.

6.2 Other

An individual TIT monitoring system is ideally suited to the detection of an uneven temperature distribution around the engine and inferring common faults which can cause this.

The effect of a broken thermocouple probe tip (Sec. 4.2) will be very evident with the expected actual temperature drop of 396°C approximately (Sec. 4.2) reflecting a drop of 371°C (0.938 × 396°C according to equation 40) in the temperature "sensed" at the terminals of the faulty probe.

Just as for the average TIT sensor (Sec. 4.3), the effect of a thermocouple short circuit to engine frame cannot be readily predicted.

Any increase in contact resistance between the thermocouple probe terminals and the standard engine loom will result in a closely proportional increase in the residual component value. Since the residual component is about 6.5 % of measured signal (0.075 ohm probe internal resistance assumed) a 0.01 ohm increase (13 %) would increase this component to 7.3 %. Extreme values of residual component, according to manufacturer's rejection limits on probe internal resistance (0.560 to 0.106 ohm at 100°C - refer Sec. 2), would be 3.9 and 9.2%.

7. Signal Conditioning Considerations for Individual Turbine Inlet Temperature Sensor

When designing signal conditioning systems it is usually not necessary to have an in-depth understanding of the transduction principle of the sensor, as it is normally a self-contained unit with defined characteristics. This is not the case for the thermocouple temperature sensing system as the complete network from hot to cold junction influences the sensor output.

In the case of the T56 engine, the TIT sensor is favourably configured to allow the measurement of individual thermocouple temperatures. Convenient connection of chromel and alumel wires to individual thermocouple probes can be made directly at the probe terminals without any modification to the standard TIT sensor circuit. The high ratio (14:1 for a nominal 0.075 ohm probe internal resistance) of loom input resistance to probe internal resistance means that about 93.5 % of the signal developed at the probe terminals is directly proportional to the temperature of the thermocouple hot junction. The very low source resistance of the thermocouple probe (nominally 0.075 ohm at 1000°C engine operating temperature) means that a measuring circuit normal mode input resistance greater than about 70 ohm would produce less than 1.0°C error in the temperature measured by the Indicator circuit. In practice the measuring circuit input resistance would be made much higher than this so that connection of the individual TIT measuring circuit would have negligible effect on the Indicator circuit output.

Common mode signals (between signal wires and aircraft ground) in aircraft thermocouple installations are usually very significant and may far exceed the normal (differential) mode signals. Some fundamental properties of thermocouple circuits tend to accentuate this effect:

(a) Ordinary thermocouple wire does not meet the desired shielded twisted-pair conductor criteria for good common mode rejection.

(b) The difference in resistivity of the two thermocouple wires results in a resistance imbalance between the signal wires.

The unbalanced lead resistances can easily change common mode to normal mode signals through the action of extraneous leakage paths to ground. Use of short cable runs to the signal conditioning amplifiers tends to reduce this effect. High common mode signal rejection is a major requirement of an individual TIT measuring system.

The low output voltage of the thermocouple (about 40 microvolt/°C for type K chromel-alumel thermocouples) renders even a small amount of noise significant. Low pass filtering of some form is usually essential to reduce the effect of extraneous noise on the temperature measurements.

Multi-channel thermocouple temperature measuring systems usually aim to reference all measurements to the same cold junction temperature. To achieve this, it is essential that the extremities of the chromel and alumel wires at the "cold" end of the TIT sensor circuit be kept at the same temperature. Most thermocouple circuits make use of an isothermal environment in which the cold junction temperature can vary over a range. The cold junction temperature is sensed and a compensating voltage is generated to make the cold junction behave as if it were held at a constant reference temperature (usually 0°C). In most systems the cold junction is established at the input to the signal conditioning unit which provides amplification of the sensed signals. It is possible to locate the cold junction remote from the signal conditioning unit as illustrated in Fig. 13. This arrangement is suited to harsh environments, such as that for direct engine mounting, and allows connection to a remote signal conditioner via standard copper conductors.

8. Conclusions

(a) The internal resistance of the turbine inlet temperature thermocouple probes for the T56 engine increases by about 25 % from room temperature to 1000°C engine operating temperature.

(b) An AC ratio measurement technique is capable of providing accurate and instantly available measurements of probe internal resistance even when temperature variations are present across the probe. This technique could be implemented in a flight line tester for checking probe electrical integrity.

(c) Accurate turbine inlet temperature averaging is achieved in the standard T56 installation by using interconnecting looms with closely matched resistance parameters. Measurements on a new loom indicated matching to within 0.4 % of mean values.

(d) The analysis of the multiple thermocouple junction circuit was simplified by defining an equivalent circuit for a single junction and using superposition to determine the net effect of multiple junctions.

(e) To a good approximation the standard turbine inlet temperature sensor for the T56 engine measures the average of the two loom average thermocouple temperatures (for thermocouples 1 to 9 and 10 to 18 respectively). This relationship is also valid if some thermocouples are open circuit provided the temperatures of such thermocouples are excluded from the average.

(f) The loom input resistance to probe internal resistance ratio of 14:1 (typical of units whose resistance was measured), means that the conveniently accessible probe terminals are a suitable source of inputs for an individual thermocouple probe temperature measuring system.

(g) The shunting effect of the thermocouple loom results in the terminal output of a given thermocouple probe containing a residual component comprising inputs from other probes. The magnitude of the residual component is nominally 6.5 % of the signal appearing at the probe terminals, but extremes corresponding to the manufacturer's rejection limits on probe internal resistance would be 3.9 and 9.2 %.

(h) The side effect of an open circuit probe on the temperatures deduced from signals measured at the terminals of other probes is negligible.

(i) The magnitude of the residual component is proportional to the thermocouple probe internal resistance. Contact resistance between the probe terminal studs and the lugs mounted on the looms can increase the effective probe internal resistance.

(j) A derived transfer coefficient matrix allows actual probe temperatures to be simply calculated from measured probe temperatures and could be used to provide the best estimate of actual temperatures sensed by individual thermocouple probes.

(k) In designing a system for measurement of the individual turbine inlet temperatures sensed by the thermocouple probes, special attention needs to be given to the signal conditioning input circuits and their interconnection with the probes. It is particularly important that interference with the standard turbine inlet temperature sensor be avoided.

Acknowledgment

The following contributions by DSTO AMRL staff to the work associated with this paper are gratefully acknowledged:

Mr Frank Skidmore and Mr David Parslow for providing insights into T56 engine problems and for providing results (Fig. 12) of tests they planned and conducted at the Qantas T56 engine test facility in Sydney on the measurement of individual thermocouple probe temperatures.

Mr Don I. Mooney for his input to this paper in the signal conditioning requirements area from work he has undertaken in the closely associated electronics system design study for individual turbine inlet temperature measurement.

Mr Ray B. Maier for his development and implementation of an AC ratio technique (Appendix 1) for measuring thermocouple probe internal resistance (at both room temperature and simulated in-flight engine operating temperature) and associated loom resistances.

References

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Appendix 1

Thermocouple Probe Resistance Measurement at Elevated Temperature

The thermocouple probe resistance at elevated temperatures was measured with the aid of an electric furnace and an AC ratio measuring circuit (Figs. 14a and 14b). The frequency of AC excitation chosen was 1 kHz, a value which was comfortably above the frequency of any thermally induced voltage components generated by the probe and below a value where reactive impedances may be significant. As the probe internal resistance is very low (less than 0.1 ohm), considerable care had to be taken to ensure that measurement errors were not introduced by added contact resistance.

From Fig. 14b it follows that:

$$R_T = \frac{R_S V_T}{V_{IN} - V_T}$$
$$= \frac{R_S}{\frac{V_{IN}}{V_T} - 1}$$

where R_T is the internal resistance of the probe;

R_S is series resistance (set to 50 ohm);

V_{IN} is AC excitation voltage (set to 15 VRMS);

V_T is the AC voltage measured across the probe terminals.

In this case $V_T << V_{IN}$ and the following is valid:

$$R_T \approx \frac{R_S V_T}{V_{IN}}$$

R_S was required to be capable of dissipating 4.5 watt.

The method of connecting the probe to the furnace is illustrated in Fig. 15. An attempt was made to approximate the temperature gradient expected across the probe in flight. The approximate temperature variation across the probe at 1000°C (a representative in-flight figure) is illustrated in Fig. 16.

A summary of the test results is provided in Table 8. As expected, the probe resistance increased with temperature. The magnitude of the increase is about 25% from 20°C to 1000°C.

Table 1: Measured Internal Resistance of Thermocouple Probes

Thermocouple Probe	Resistance (ohm) No. 1	Resistance (ohm) No. 2
New No. 1	0.0520	0.0552
New No. 2	0.0541	0.0586
New No. 3	0.0544	0.0604
Old No. 1	0.0654	0.0684
Old No. 2	0.0658	0.0624
Old No. 3 *	0.0594	0.0611

* Non air-cooled version

Table 2: Measured Resistance of Indicator Section (Inputs 1 to 9) of New Loom

Chromel Input to Output		Chromel Input to Input		Alumel Input to Output		Alumel Input to Input	
X01 - XJ	1.436			Y01 - YJ	0.600		
X02 - XJ	1.437	X02 - X01	1.343	Y02 - YJ	0.601	Y02 -Y01	0.557
X03 - XJ	1.437	X03 - X01	1.344	Y03 - YJ	0.604	Y03 -Y01	0.560
X04 - XJ	1.436	X04 - X01	1.343	Y04 - YJ	0.602	Y04 -Y01	0.558
X05 - XJ	1.438	X05 - X01	1.345	Y05 - YJ	0.602	Y05 -Y01	0.558
X06 - XJ	1.439	X06 - X01	1.347	Y06 - YJ	0.602	Y06 -Y01	0.558
X07 - XJ	1.438	X07 - X01	1.344	Y07 - YJ	0.602	Y07 -Y01	0.558
X08 - XJ	1.439	X08 - X01	1.346	Y08 - YJ	0.602	Y08 -Y01	0.558
X09 - XJ	1.438	X09 - X01	1.346	Y09 - YJ	0.601	Y09 -Y01	0.556

All resistance values are in ohm.

Wire designation conforms to Fig. 4a.

Table 3: Transfer Coefficients for Standard Temperature Averaging Sensor

$$T_H = a_1T_1 + a_2T_2 + \ldots + a_{18}T_{18}$$

n	1	2	3	4	5	6	7	8	9
a_n	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556
n	10	11	12	13	14	15	16	17	18
a_n	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556

Output Resistance = 0.601 ohm

Table 4: Transfer Coefficients for Standard Temperature Averaging Sensor with No. 1 Thermocouple Probe Open Circuit

$$T_H = a_1 T_1 + a_2 T_2 + \ldots + a_{18} T_{18}$$

n	1	2	3	4	5	6	7	8	9
a_n	0.0000	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621
n	10	11	12	13	14	15	16	17	18
a_n	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559

Output Resistance = 0.6027 ohm

Table 5: Transfer Coefficients for Signal Sensed at Terminals of Open Circuit Thermocouple Probe No. 18

$$T_{18M} = a_1 T_1 + a_2 T_2 + \ldots + a_{18} T_{18}$$

n	1	2	3	4	5	6	7	8	9
a_n	0.0059	0.0059	0.0059	0.0059	0.0059	0.0059	0.0059	0.0059	0.0059
n	10	11	12	13	14	15	16	17	18
a_n	0.1184	0.1184	0.1184	0.1184	0.1184	0.1184	0.1184	0.1184	0.0000

Table 6: Transfer Coefficient Matrix Relating Measured to True Thermocouple Temperatures

$$T_M = AT_T$$

$A \quad =$

+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346	+0.0077
+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0004	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.0077	+0.9346

Table 7: Inverse Transfer Coefficient Matrix Relating True to Measured Thermocouple Temperatures

$$T_T = \overline{A} T_M$$

$\overline{A}$ =

+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705	-0.0084
-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	-0.0084	+1.0705

Table 8: Rise in Thermocouple Probe Internal Resistance with Temperature

Probe Under Test	Probe 1		Probe 2		Probe 3
Element Under Test **	A	B	A	B	A
Measured Internal Resistance at 20°C (ohm)	0.0654	0.0684	0.0658	0.0624	0.0594
Measured Internal Resistance at 1000°C (ohm)	0.0810	0.0852	0.0824	0.0788	0.0747
Resistance Increase (ohm)	0.0156	0.0168	0.0166	0.0164	0.0153
Per Cent Increase	23.9	24.6	25.2	26.3	25.8
Average Per Cent Increase	25.2				

** Each probe has two "elements" (thermocouple circuits) for connection to the Temperature Datum and Indicator circuits respectively. However the roles of the individual elements are reversed for the two looms (ie. if a given side of a thermocouple is used in the Temperature Datum circuit when installed on the 1 - 9 probe side of the engine it would be used in the Indicator circuit if installed on the 10 - 18 probe side of the engine).

Note: Probes 1 and 2 were in good condition but had been in service (period unknown). Probe 3 was new and only one of its elements was tested.

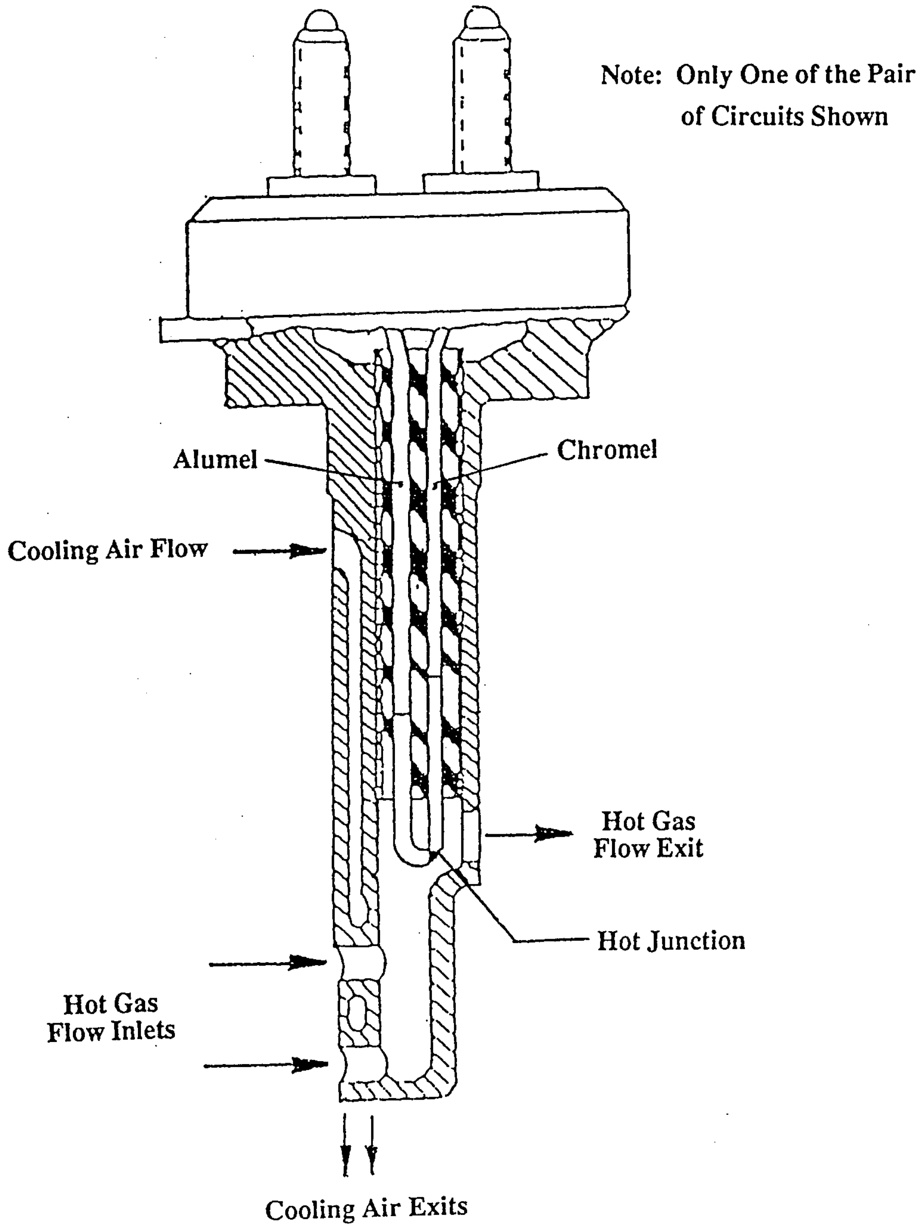


FIG. 1 : Air-Cooled Type Thermocouple Probe for T56 Engine

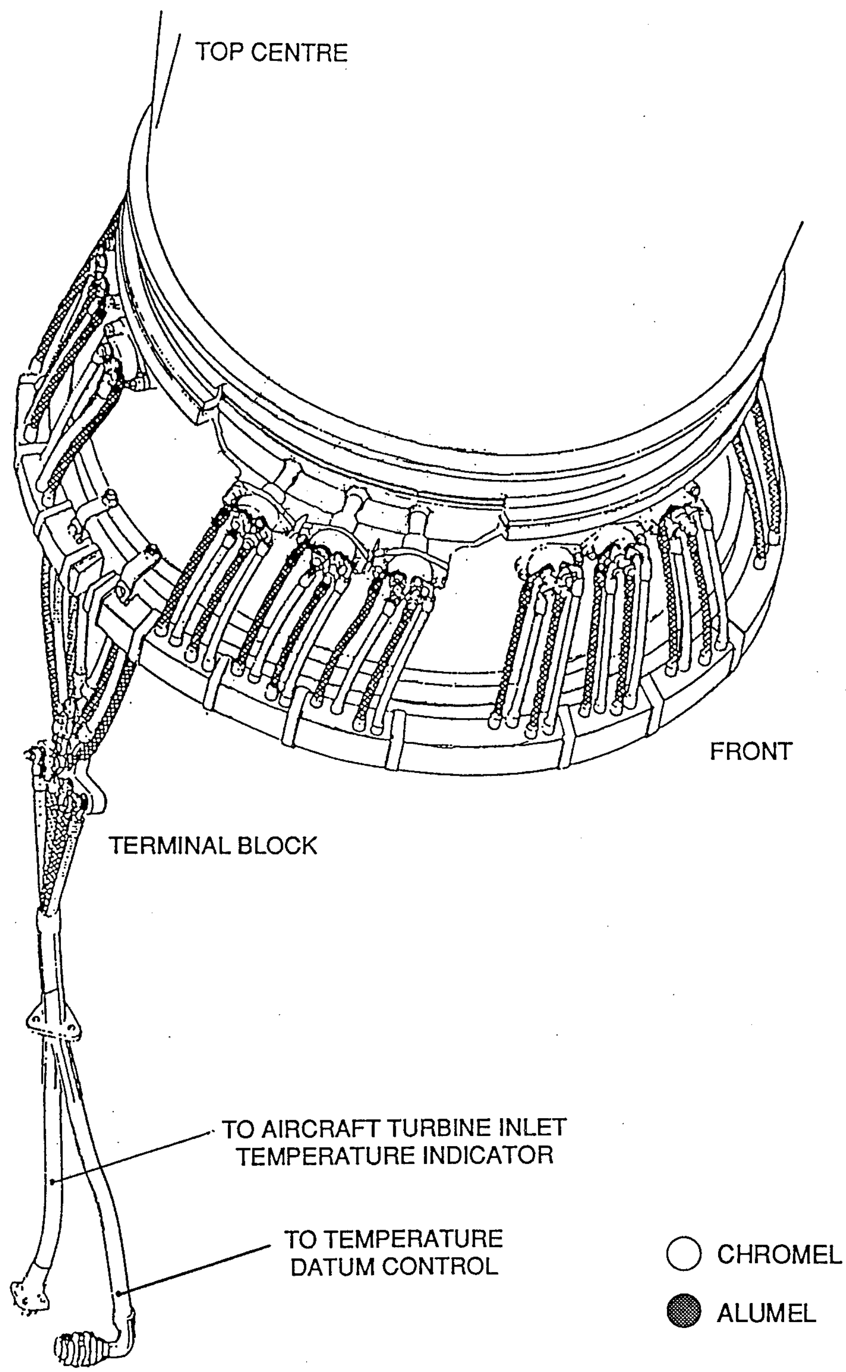


FIG. 2 : Thermocouple Installation on T56 Engine

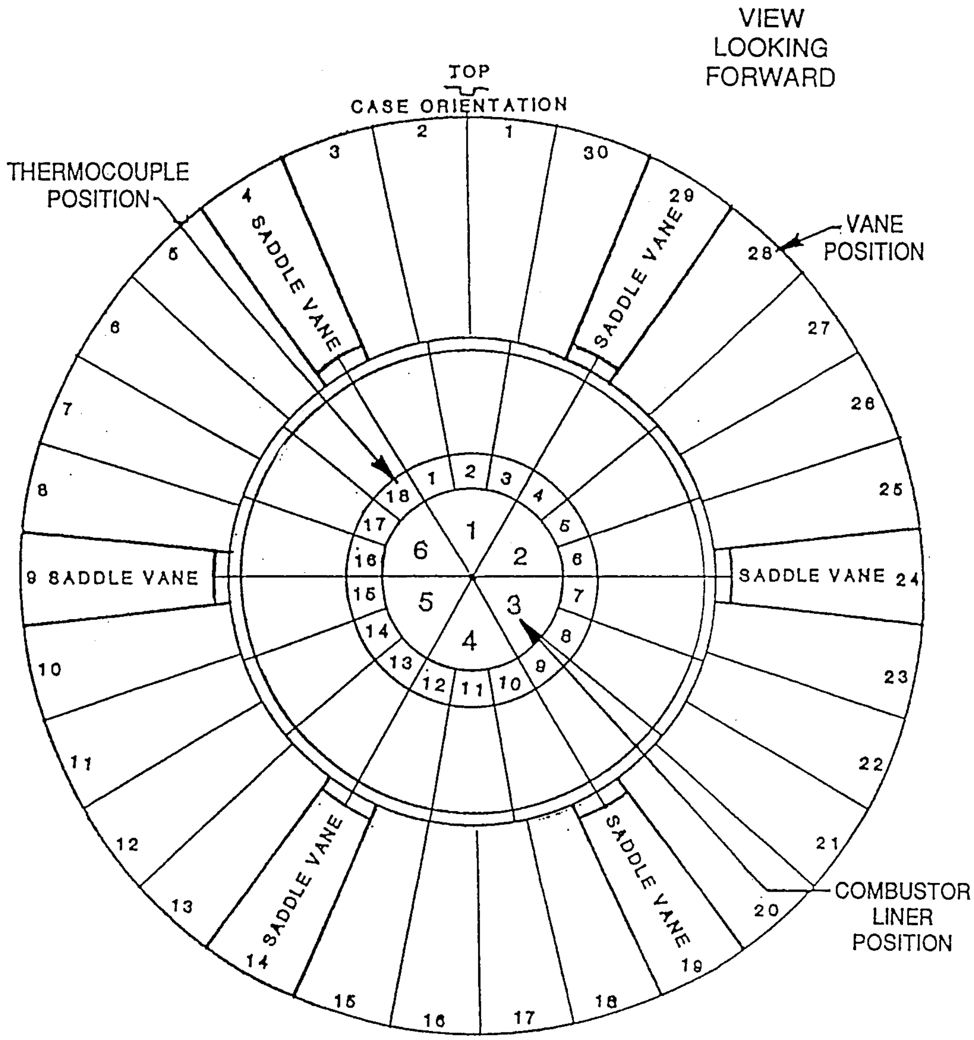
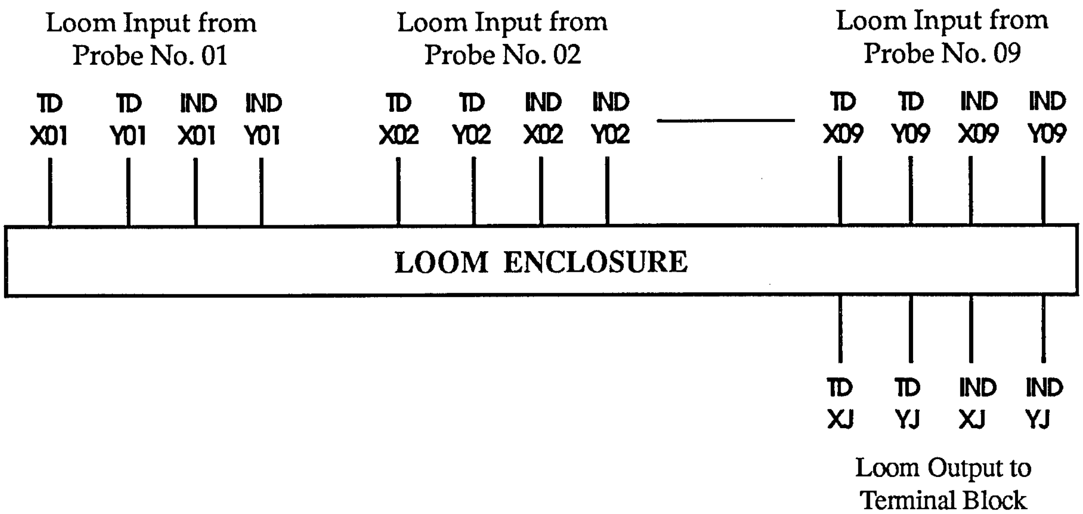
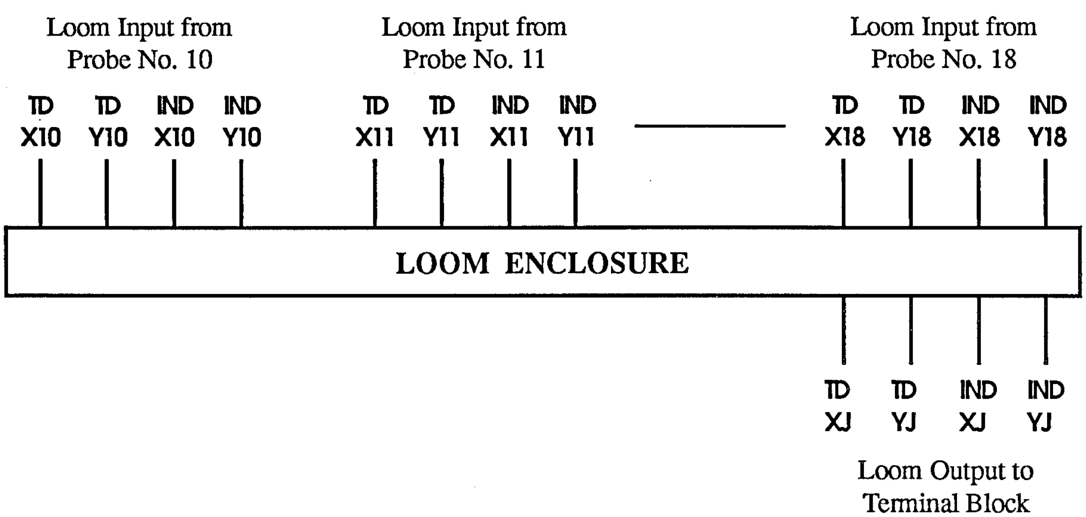


FIG. 3 : Thermocouple Probe and Combustor Liner Radial Positions



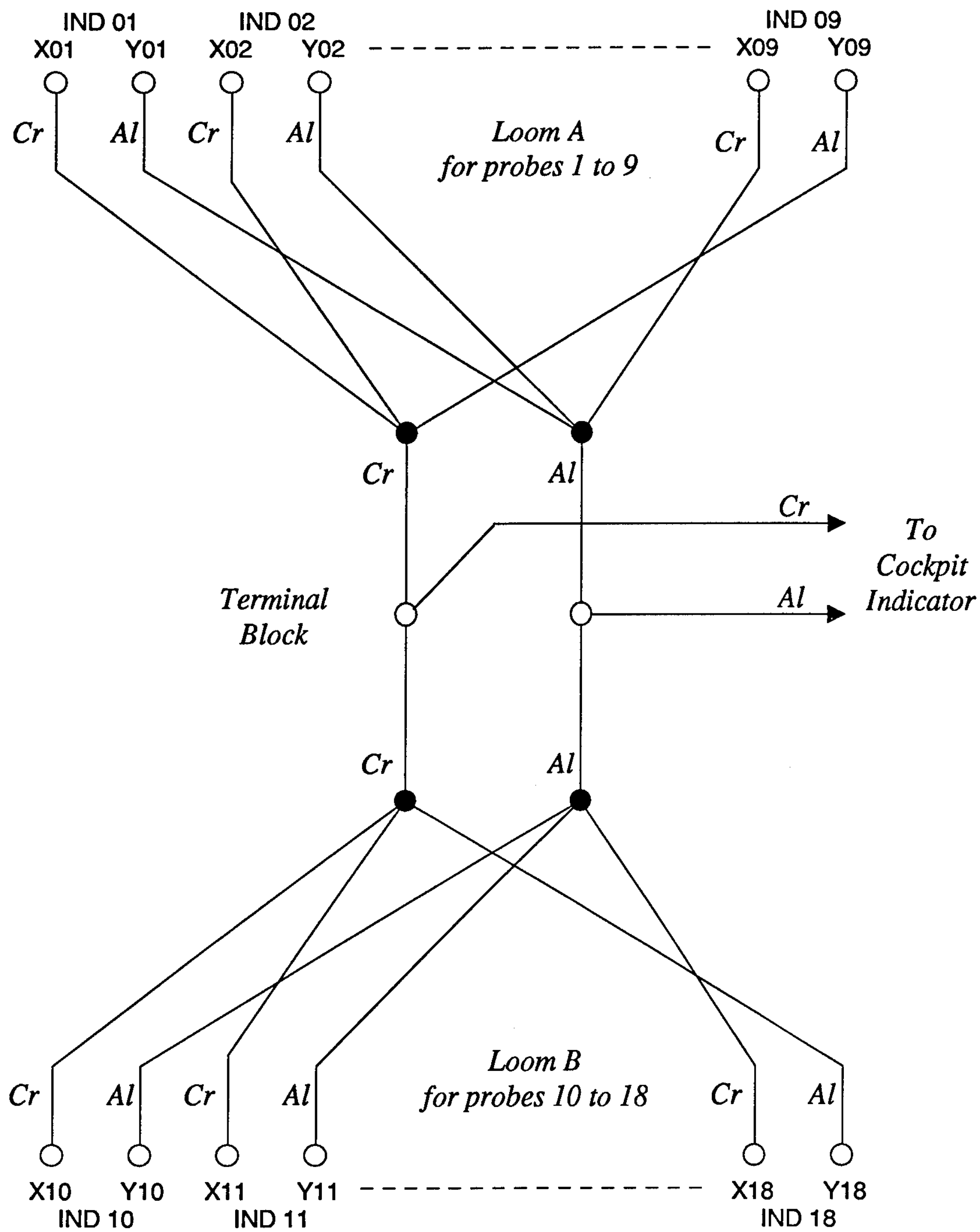
(a) **Loom for Thermocouple Probes 01 to 09**



(b) **Loom for Thermocouple Probes 10 to 18**

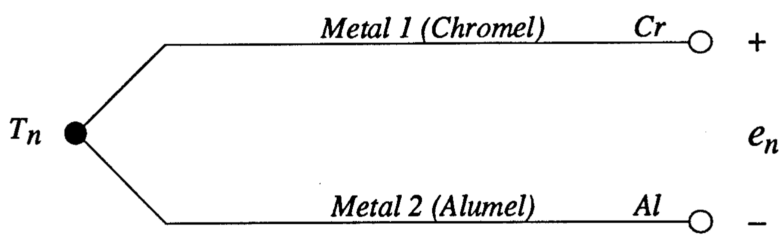
Labels:	X →	chromel	TD →	Temperature Datum circuit
	Y →	alumel	IND →	Indicator circuit

FIG. 4: Layout of Thermocouple Temperature Averaging Looms

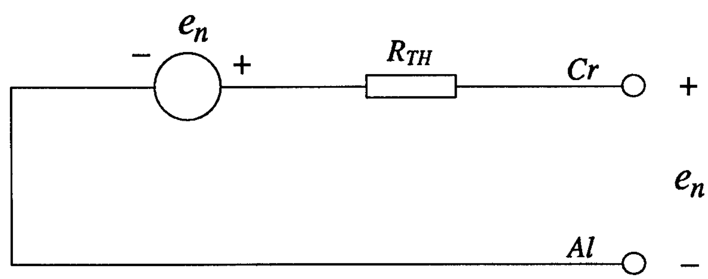


Note: IND 01 to IND 18 terminal pairs are connected to probes 01 to 18.

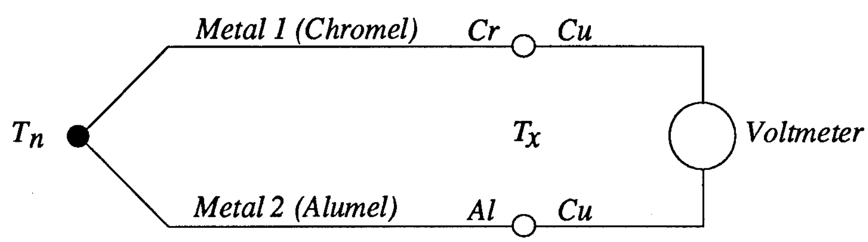
FIG. 5 : Indicator Loom Electrical Connections



(a) Open Circuit Thermocouple



(b) Equivalent Circuit of Open-Circuit Thermocouple



(c) Measurement of Open-Circuit Thermocouple Voltage

FIG. 6 : Isolated Thermocouple Characteristics

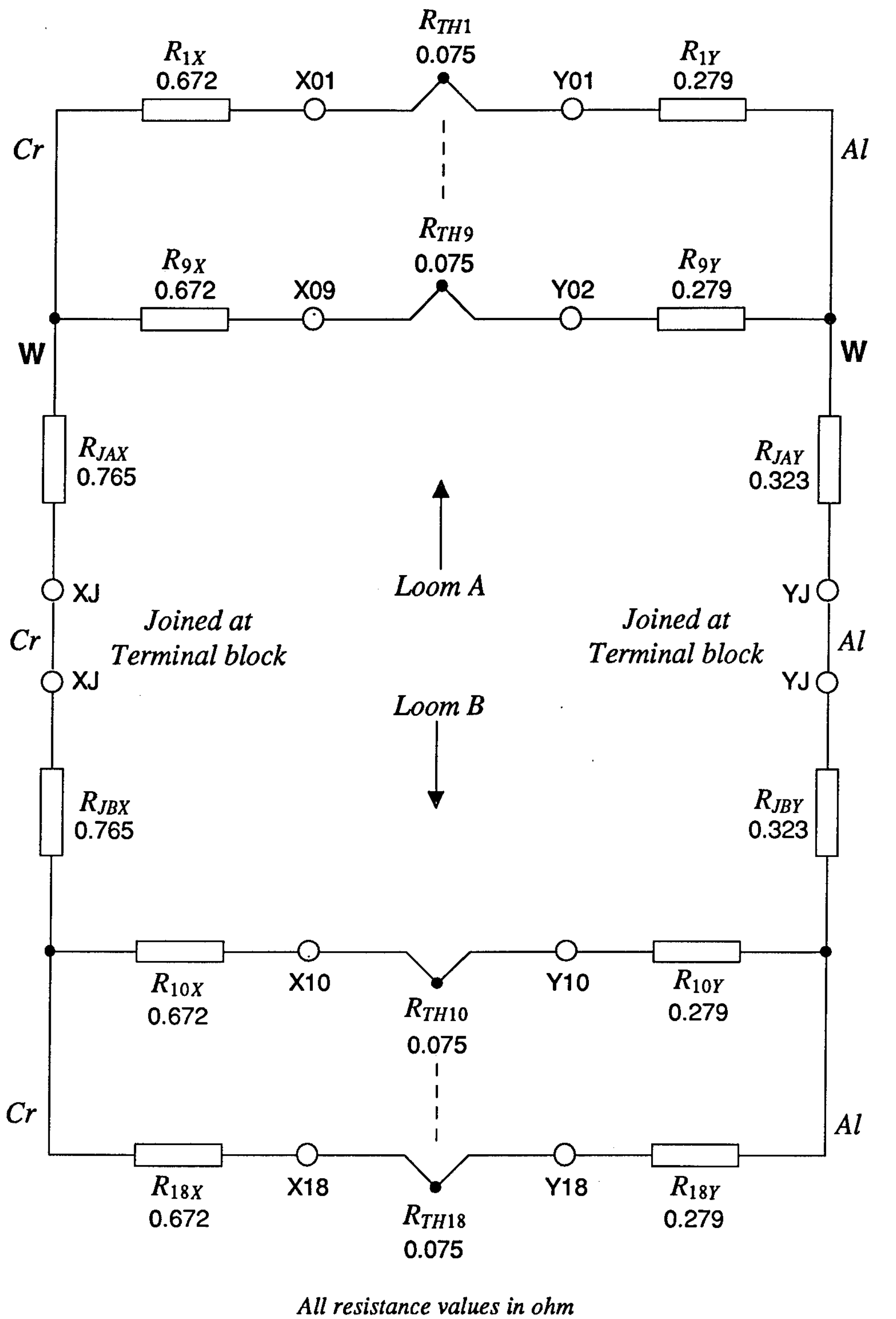
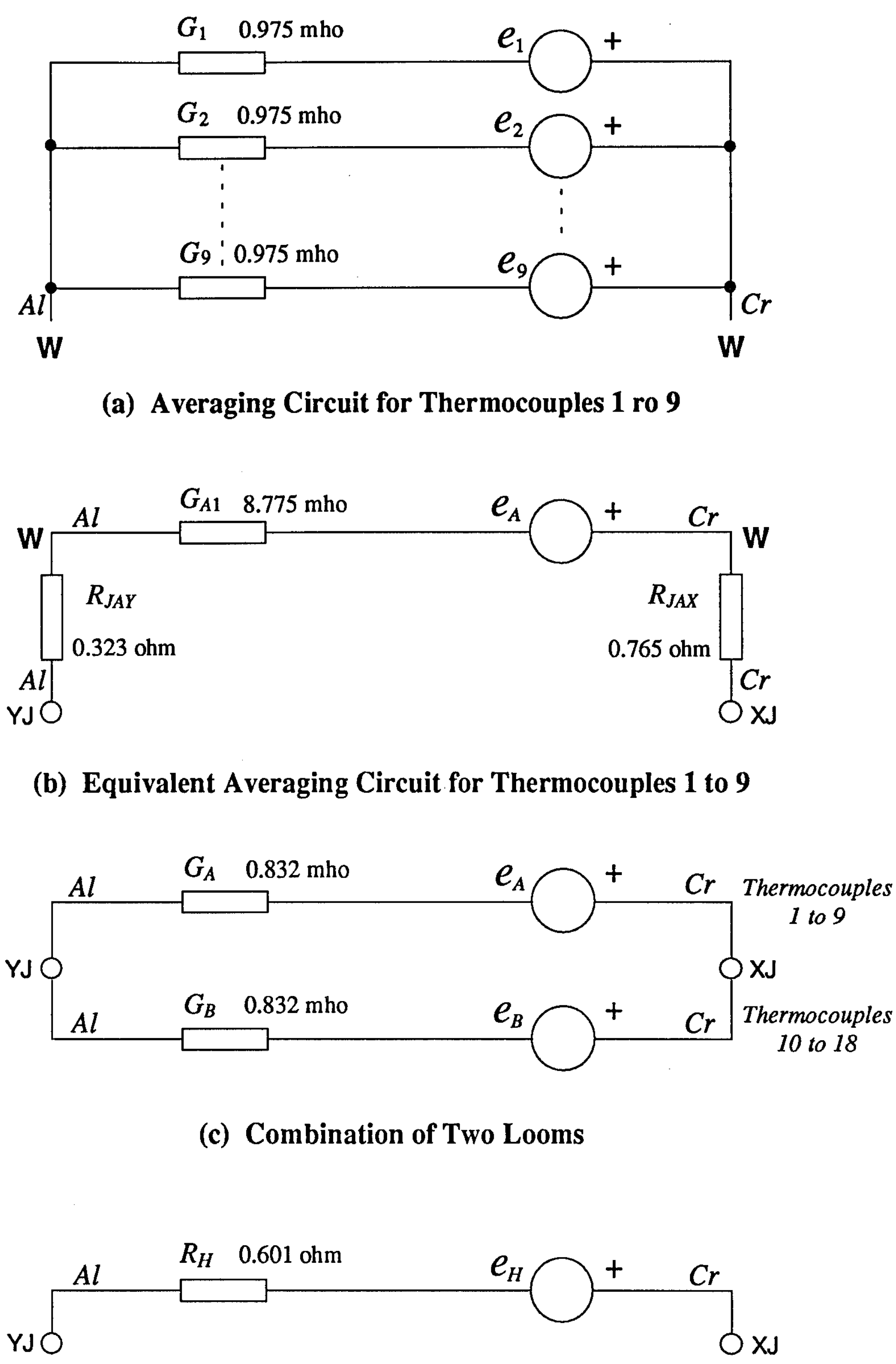


FIG. 7 : T56 Thermocouple Equivalent Electrical Circuit



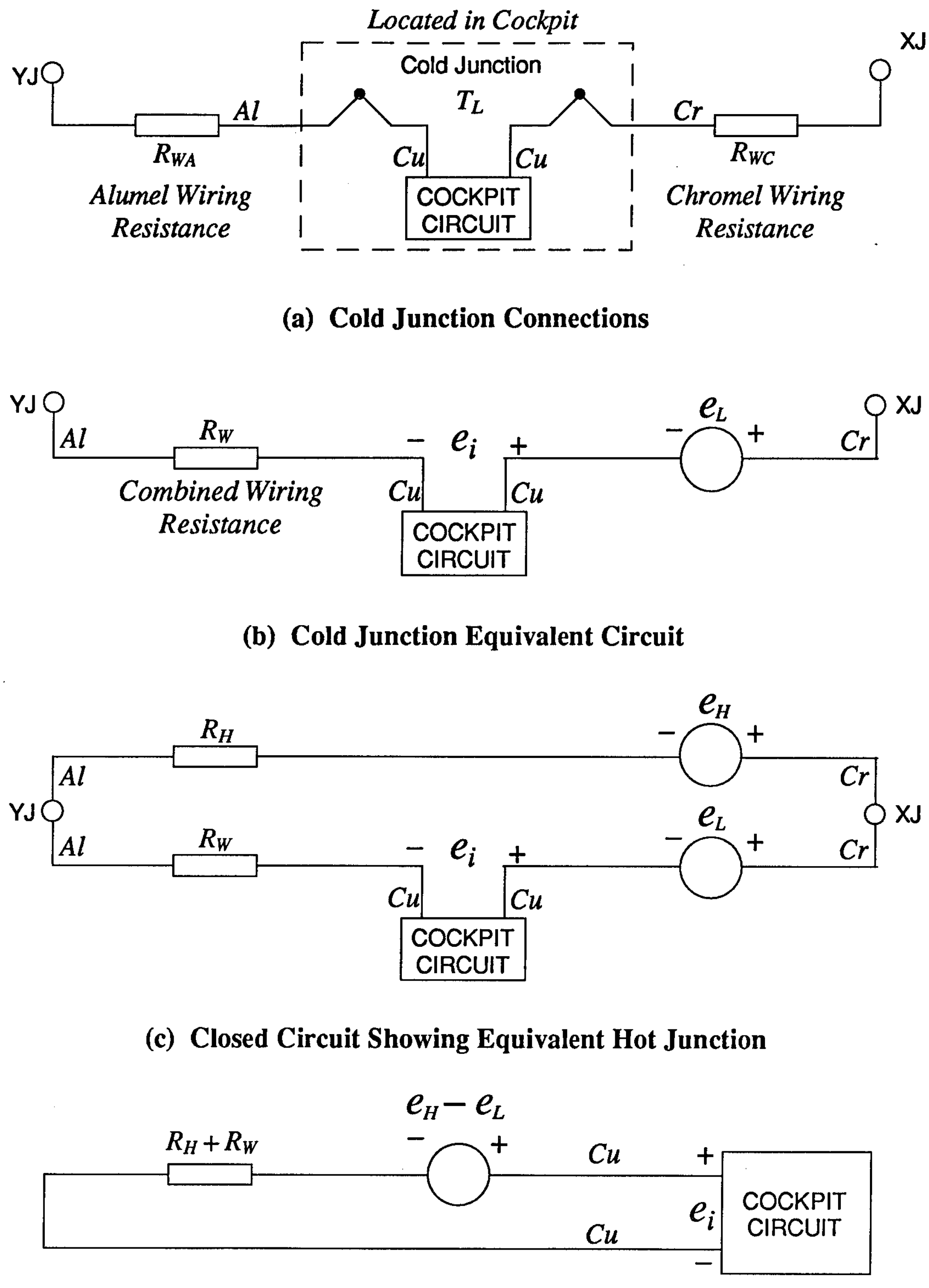
(a) Averaging Circuit for Thermocouples 1 ro 9

(b) Equivalent Averaging Circuit for Thermocouples 1 to 9

(c) Combination of Two Looms

(d) Equivalent Hot Junction

FIG. 8 : Derivation of Equivalent Hot Junction



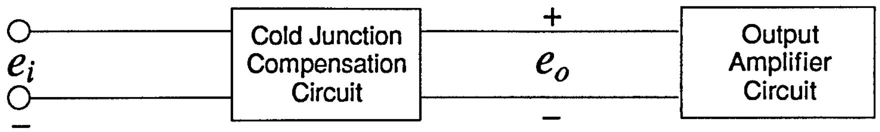
(a) Cold Junction Connections

(b) Cold Junction Equivalent Circuit

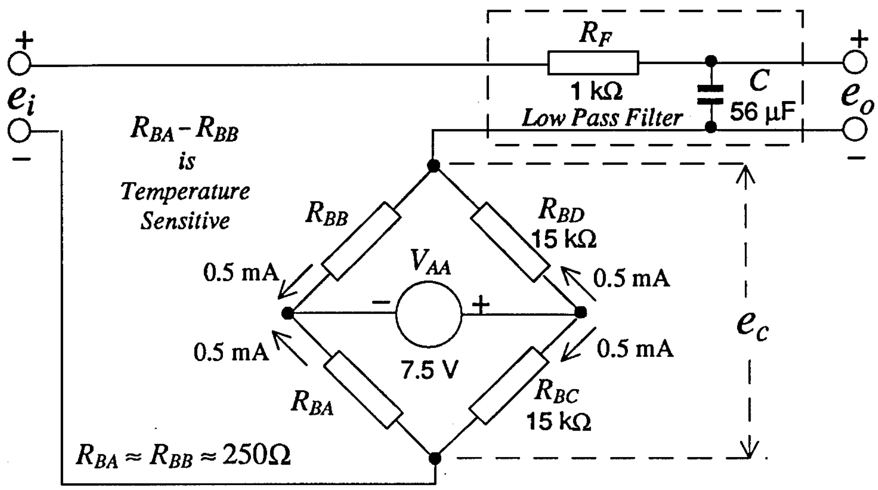
(c) Closed Circuit Showing Equivalent Hot Junction

(d) Closed Circuit Showing Net emf

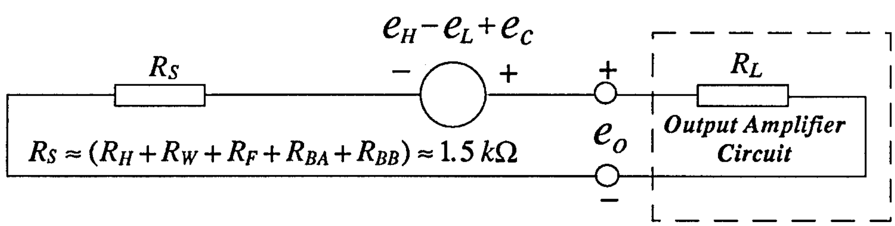
FIG. 9 : Closed Circuit Thermal emf



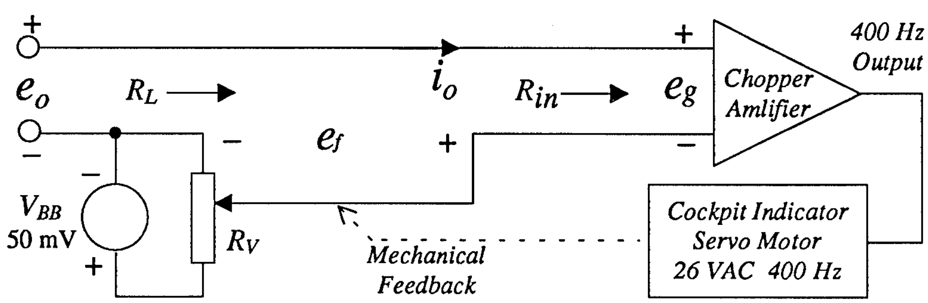
(a) Cockpit Circuit Block Schema



(b) Simplified Cold Junction Compensation Circuit

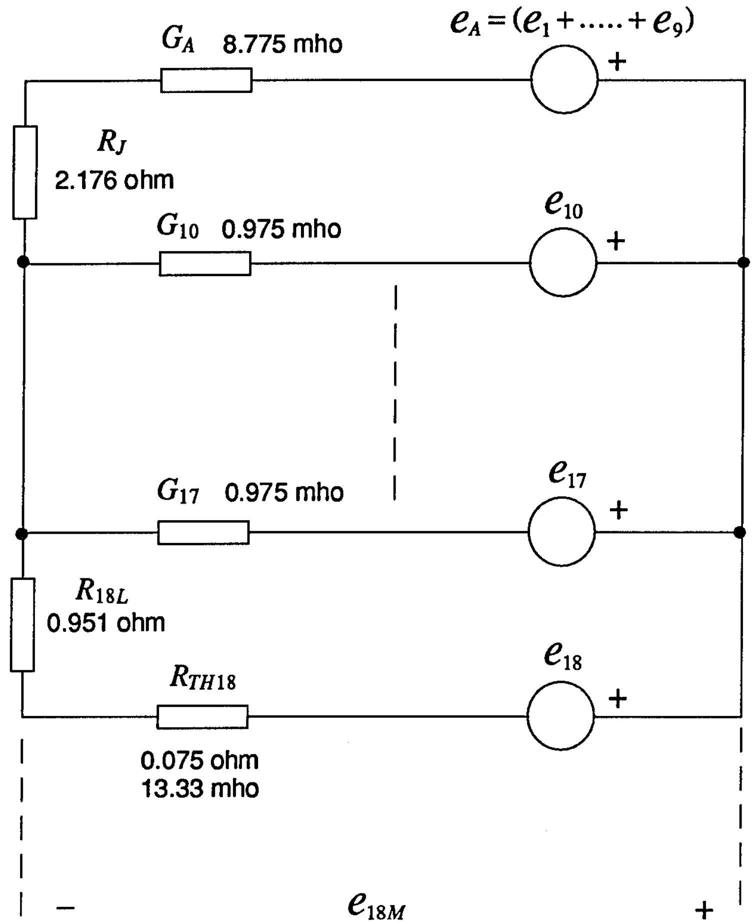


(c) Equivalent Low Level Signal Circuit



(d) Output Feedback Amplifier Circuit

FIG. 10 : Cockpit Indicator Circuit Functions

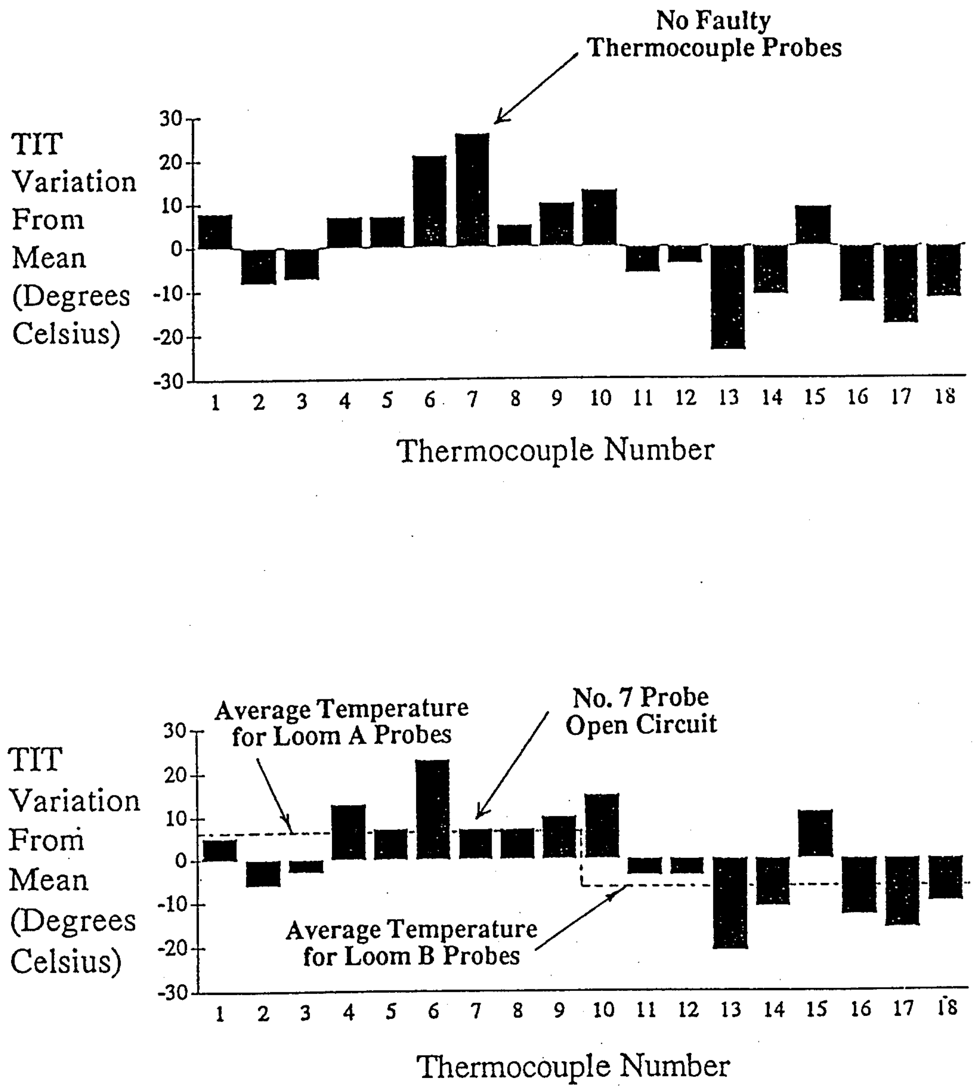


Notes: $R_J = R_{JAX} + R_{JAY} + R_{JBX} + R_{JBY}$

$R_{18L} = R_{18X} + R_{18Y}$

R_{TH18} *is the internal resistance of thermocouple No. 18.*

FIG. 11 : Equivalent Circuit for Calculating Thermocouple 18 Terminal Voltage



Individual TIT Monitoring System Test Results

FIG. 12 : Temperature Sensed by Open Circuit Thermocouple Probe

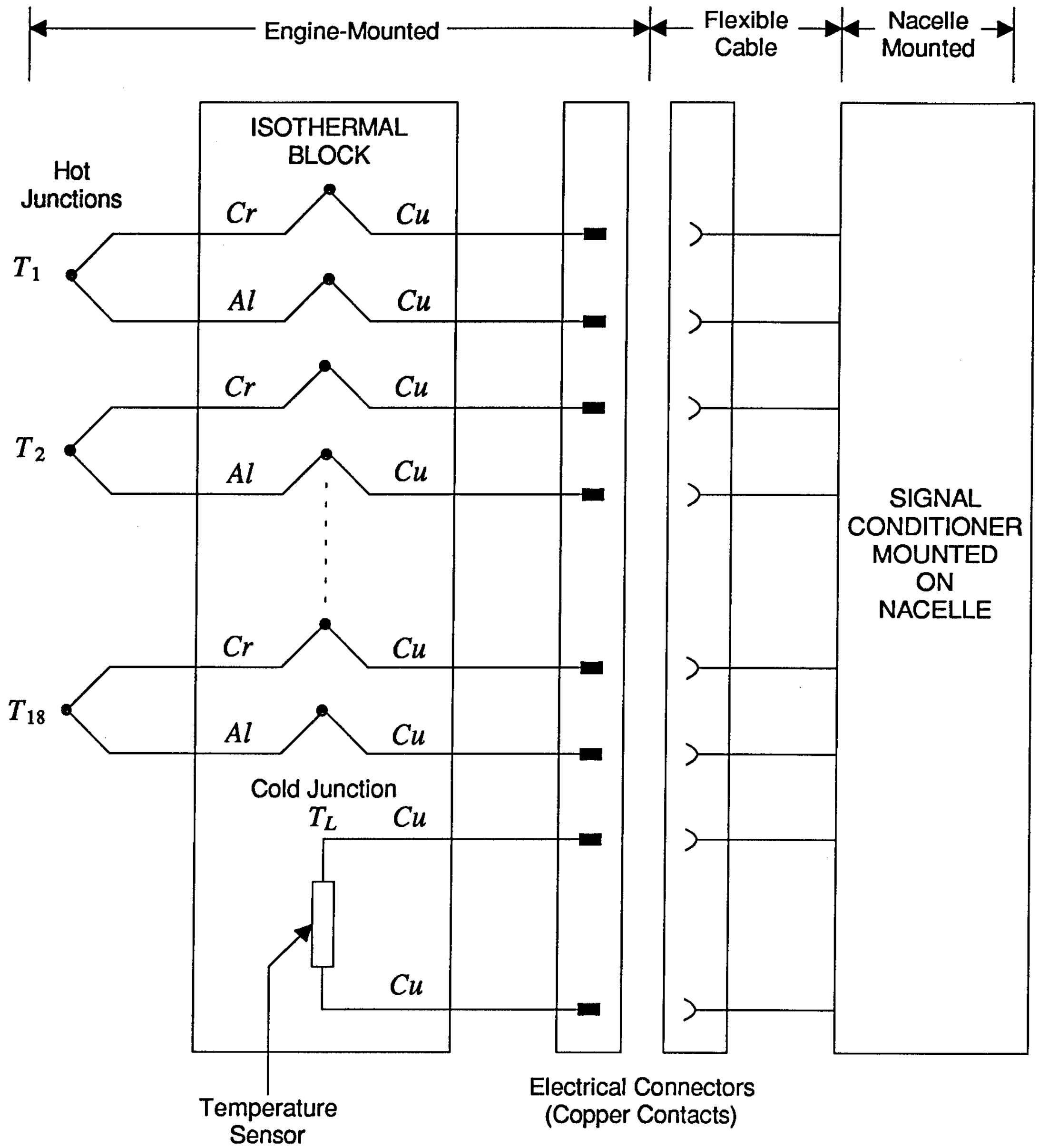
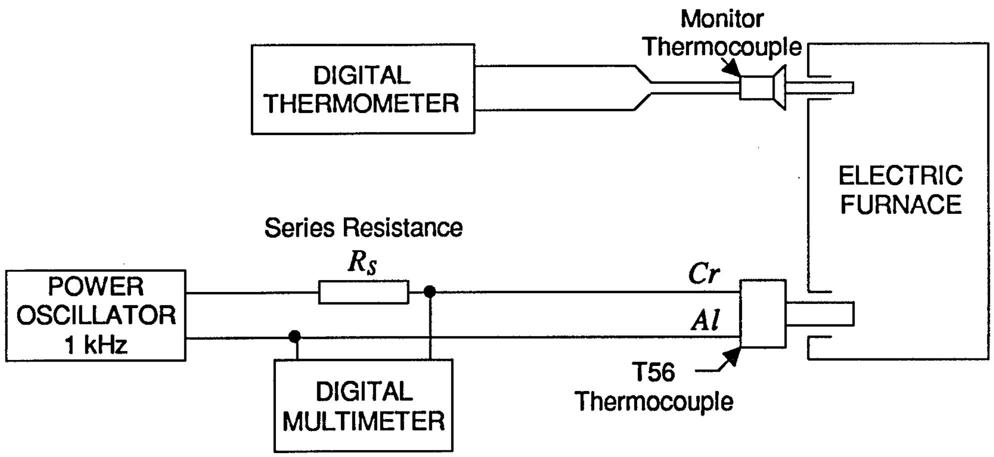


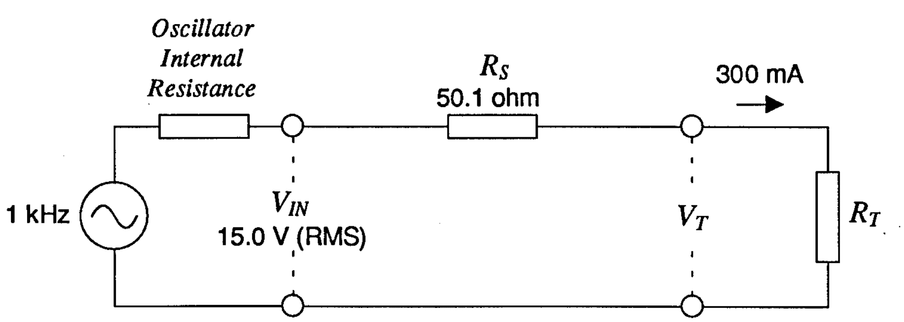
FIG. 13 : Configuration with Engine-Mounted Cold Junction



Component Details:

Power Oscillator	Ling Model TPO 25
Digital Thermometer	Fluke Model 2190A
Digital Multimeter	Fluke Model 8810A
Electric Furnace	C.T. Moloney 1100°C, 240 VAC/ 10 A, 3250 cc capacity
Series Resistor	22 x 1.1 kohm (50 ohm effective), metal film, 0.25 watt
Monitor Thermocouple	Chromel/Alumel (Type K), reconditioned

(a) Test Arrangement for Probe Resistance Measurement



(b) AC Voltage Ratio Measurement Circuit

FIG. 14 : Thermocouple Probe Internal Resistance Measurement

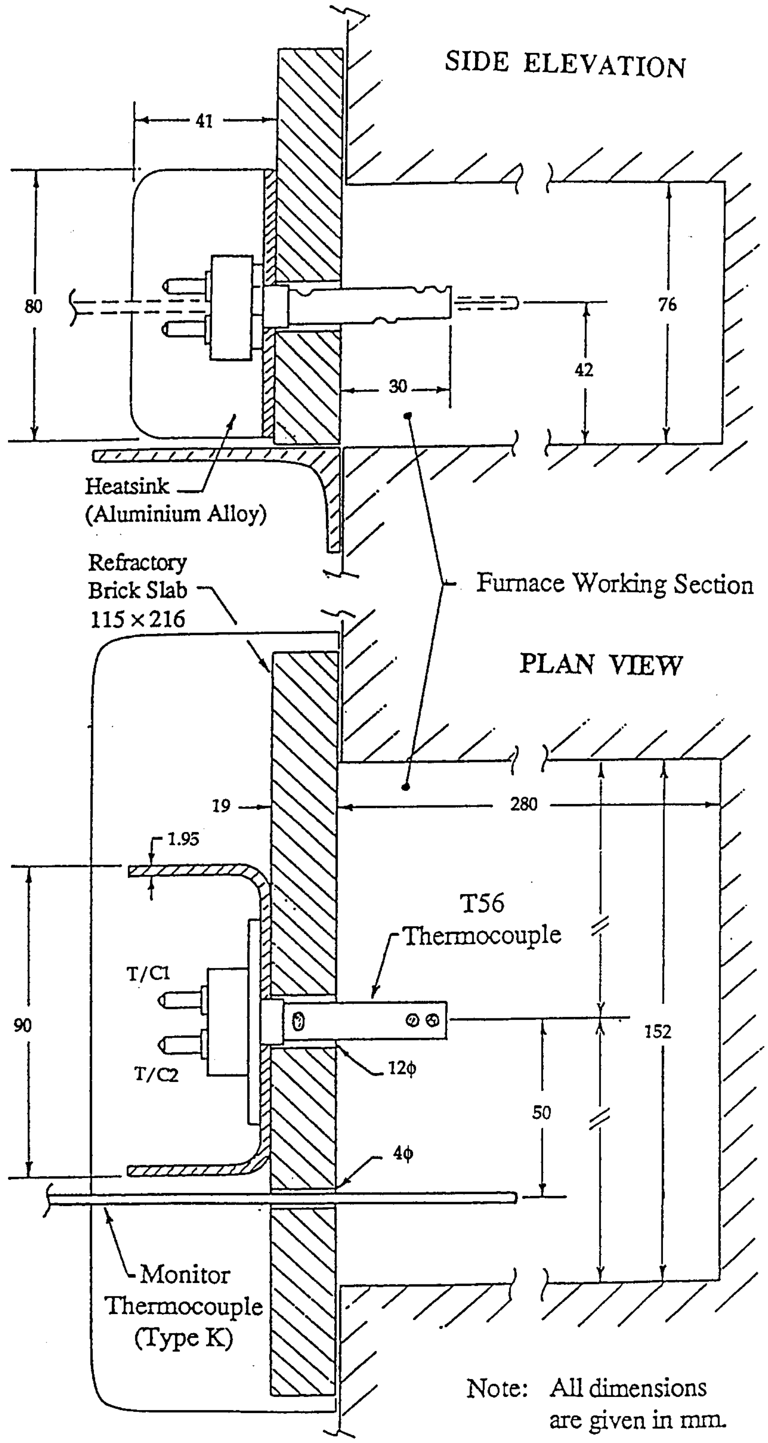


FIG. 15 : Method of Mounting Thermocouple Probe in Electric Furnace

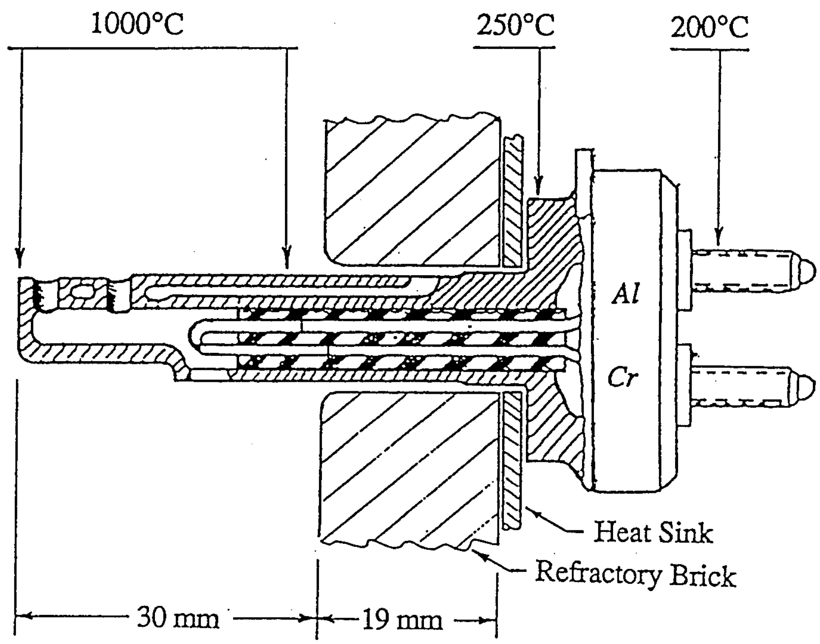


FIG. 16 : Approximate Temperature Distribution Across Probe for 1000°C Test

DSTO-TR-0095

Characteristics of the Turbine Inlet Temperature Sensing Circuit for the T56 Turbo-Prop Engine

K.F. Fraser

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AR-008-374	DSTO-TR-0095	NOVEMBER 1994	AIR 94/097

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CHARACTERISTICS OF THE TURBINE INLET TEMPERATURE SENSING CIRCUIT FOR THE T56 TURBO-PROP ENGINE	U (DOCUMENT) U (TITLE) U (ABSTRACT)	53	3

8. AUTHOR(S)	9. DOWNGRADING/DELIMITING INSTRUCTIONS
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14. DESCRIPTORS		15. DISCAT SUBJECT CATEGORIES
Allison T56 engines	Temperature measuring instruments	2105
Engine inlets	Temperature control	

16. ABSTRACT

The temperature to voltage transfer characteristics of the standard turbine inlet temperature averaging sensor for the T56 turbo-prop engine are derived using measured resistance parameters for the 18-thermocouple network. The transfer characteristics of an add-on individual thermocouple temperature sensing circuit are also derived and some of the requirements of the associated signal conditioning circuit are briefly reviewed.

PAGE CLASSIFICATION
UNCLASSIFIED

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16. ABSTRACT (CONT).

17. IMPRINT

AERONAUTICAL AND MARITIME RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER	19. WA NUMBER	20. TYPE OF REPORT AND PERIOD COVERED
DSTO Technical Report 0095	20 232J	

21. COMPUTER PROGRAMS USED

M1/9/46

22. ESTABLISHMENT FILE REF.(S)

23. ADDITIONAL INFORMATION (AS REQUIRED)